WASTE RECOVERY IN CONSTRUCTED WETLANDS USING A COMBINATION OF AQUATIC PLANT AND FISH

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การใช้ประโยชน์ของเสียในพื้นที่ชุ่มน้ำประดิษฐ์โดยใช้พืชและปลาร่วมกัน

นางสาวฐนียา เภอบางเข็ม

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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ในการศึกษาครั้งนี้ได้ทำการปล่อยน้ำเสียชุมชนซึ่งมีความเข้มข้นต่ำเข้าสู่พื้นที่ชุ่มน้ำประดิษฐ์เพื่อหาประสิทธิภาพการบำบัดของสารอินทรีย์และธาตุอาหารในระบบบำบัด คือ พื้นที่ชุ่มน้ำประดิษฐ์แบบมีปลาและไม่มีปลา รวมถึงทำการเปรียบเทียบประสิทธิภาพการบำบัดแต่ละแบบ กับระบบบำบัดแบบบ่อผึ่งที่มีปลาและไม่มีปลา นอกจากนี้การศึกษานี้ยังทำการหาผลผลิตของปลาและพืชที่ปลูกในระบบพื้นที่ชุ่มน้ำประดิษฐ์ และสุดท้ายได้นำผลการศึกษาทั้งหมดมาใช้ในการพัฒนาแบบจำลองความสัมพันธ์ระหว่างพืชน้ำ ปลา และสิ่งมีชีวิตขนาดเล็กบางประเภทในระบบพื้นที่ชุ่มน้ำประดิษฐ์แบบไหลผ่านพื้นผิวในการบำบัดน้ำเสียชุมชน จากนั้นนำข้อมูลที่ได้มาทำการพัฒนาแบบจำลองที่แสดงความสัมพันธ์ระหว่างคุณภาพน้ำ พืชน้ำ ปลา และสิ่งมีชีวิตขนาดเล็กที่อยู่ในพืชที่ชุ่มน้ำประดิษฐ์แบบไหลผ่านพื้นผิวที่บำบัดน้ำเสียชุมชน น้ำเสียปล่อยเข้าระบบที่ภาระบรรทุกอินทรีย์ 10, 16, 31, และ 63 กิโลกรัมบีโอดีต่อแฮคแตร์ต่อวัน หลังจากทำการทดลองผ่านไปสองเดือนผลการทดลองแสดงให้เห็นว่าประสิทธิภาพการบำบัดสารอินทรีย์และธาตุอาหารระหว่างพื้นที่ชุ่มน้ำประดิษฐ์ที่เลี้ยงปลาและไม่เลี้ยงปลามีค่าไม่แตกต่างกันอย่างมีนัยสำคัญ โดยประสิทธิภาพการกำจัดซีโอดี บีโอดี แอมโมเนียไนโตรเจน โอโธฟอสฟอรัสและของแข็งทั้งหมดของพื้นที่ชุ่มน้ำประดิษฐ์ทั้งสองแบบอยู่ในช่วงระหว่างร้อยละ 18-68, 42-76, 19-89, 8-93 และ 27-77 ตามลำดับ เมื่อเปรียบเทียบผลการทดลองนี้กับระบบแบบบ่อผึ่งปรากฏว่าน้ำออกของระบบแบบบ่อผึ่งมีคุณภาพด้อยกว่าระบบบำบัดแบบบึงประดิษฐ์และน้ำเสียที่ปล่อยออกมาก็มีความขุ่นมากกว่าด้วยเนื่องมาจากสาหร่ายที่เกิดขึ้นในระบบ สำหรับผลผลิตของกกอียิปต์ในพื้นที่ชุ่มน้ำประดิษฐ์พบว่าอยู่ในช่วงระหว่าง 38-52 กรัมน้ำหนักแห้งต่อตารางเมตรต่อวัน และชีวมวลของพืชที่ผลิตได้ประมาณ 2280-3115 กรัมน้ำหนักแห้งต่อตารางเมตร นอกจากนี้กกอียิปต์สามารถดูดซึมไนโตรเจนได้ร้อยละ 1.73 และ ฟอสฟอรัสได้ร้อยละ 12 ในขณะที่ปลานิลที่เลี้ยงในระบบพื้นที่ชุ่มน้ำประดิษฐ์มีน้ำหนักเฉลี่ย 60 กรัมต่อตัว

จากผลการศึกษาได้มีการนำไปพัฒนาแบบจำลองโดยใช้หลักการทางอุณหพลศาสตร์ซึ่งเรียกกันว่า “เอ็มเมอจี” ซึ่งวิธีการนี้เป็นระบบการวัดค่าการเจริญเติบโตของแต่ละหน่วยและอธิบายในรูปของพลังงาน ตารางการวิเคราะห์พลังงานที่สะสมถูกนำมาใช้ในการศึกษาประสิทธิภาพของระบบพื้นที่ชุ่มน้ำประดิษฐ์ หลังจากนั้นได้นำตารางที่สร้างขึ้นมาเพื่อใช้ในการเปรียบเทียบ

ประสิทธิภาพของผลิตผลที่เกิดขึ้นและประสิทธิภาพของระบบบำบัด จากผลการศึกษาแสดงว่าประสิทธิภาพของผลิตผลพืชมีค่าสูงสุดประมาณร้อยละ 6.55 ในระบบบำบัดชุดที่ 1 (ภาระบรรทุกอินทรีย์ 10 กิโลกรัมบีโอดีต่อแฮคแตร์ต่อวัน) นอกจากนี้ประสิทธิภาพของผลิตผลปลามีค่าสูงสุดในระบบบำบัดชุดที่ 2 (ภาระบรรทุกอินทรีย์ 16 กิโลกรัมบีโอดีต่อแฮคแตร์ต่อวัน) ด้วยประสิทธิภาพการถ่ายเทพลังงานเท่ากับร้อยละ 70 ท้ายที่สุดเมื่อพิจารณาถึงวัตถุประสงค์หลักของระบบบำบัดแบบพื้นที่ชุ่มน้ำประดิษฐ์ ประสิทธิภาพของพลังงานสะสมในการกำจัดของเสียถูกพัฒนาขึ้นเพื่อศึกษาถึงประสิทธิภาพของการบำบัด ผลการทดลองพบว่าในระบบบำบัดชุดที่ 4 (ภาระบรรทุกอินทรีย์ 63 กิโลกรัมบีโอดีต่อแฮคแตร์ต่อวัน) มีค่าพลังงานสะสมมากที่สุดในทุกพารามิเตอร์ เนื่องจากในระบบบำบัดชุดนี้ต้องใช้พลังงานในการสะสมให้เป็นน้ำเสียมากกว่าชุดอื่น ตัวแบบจำลองทางเทอร์โมไดนามิกส์นี้สามารถประยุกต์ใช้ได้กับระบบบำบัดอื่นโดยการเปลี่ยนชนิดของปลาหรือ/และชนิดของพืชหรือ/และชนิดของน้ำเสียหรือ/และความเข้มข้นของน้ำเสียเพื่อช่วยในการออกแบบสำหรับการศึกษาในอนาคตต่อไป

สาขาวิชาวิศวกรรมสิ่งแวดล้อม ลายมือชื่อนักศึกษา____________________

ปีการศึกษา 2551 ลายมือชื่ออาจารย์ที่ปรึกษา________________

THANEEYA PERBANGKHEM : WASTE RECOVERY IN CONSTRUCTED WETLANDS USING A COMBINATION OF AQUATIC PLANT AND FISH. THESIS ADVISOR : ASST. PROF. CHONGCHIN POLPRASERT, Ph.D., 203 PP.

CONSTRUCTED WETLANDS / PAPYRUS / TILAPIA FISH / DOMESTIC WASTEWATER/ EMERGY

In this study, the pilot-scale constructed wetlands were fed with a low strength domestic wastewater to evaluate the removal efficiencies of organic and nutrients in various treatment system compartments: constructed wetland with and without fish, to compare these efficiencies with those of waste stabilization ponds with and without fish. Furthermore, the biomass productivity of fish and aquatic plant grown in treatment wetlands were investigated. Finally, the simulation model that encompasses the relationship among water quality, aquatic macrophyte, fish, and some microorganisms in the free water constructed wetland treating domestic wastewater were developed. The feed was operated, corresponding to the organic loading rate of 10, 16, 31, and 63 kg BOD/ha-d, respectively. From the two-month period of the experiment, the results showed that the organic and nutrient removal efficiencies between FWS wetlands with and without fish were not significantly different. The removal efficiencies of COD, BOD, NH_3-N, o-PO_4^{3-}, TSS for both CW ranged between 18-68%, 42-76%, 19-89%, 8-93%, and 27-77%, respectively. Compared with that of waste stabilization pond, the effluent of CW possessed a much better quality. The productivity of papyrus in CW was found to be in the range of

38-52 g dry weight/m^2-d and the plant biomass generation can be estimated between 2280-3115 g dry weight/m^2. In addition, papyrus can be achieved nitrogen uptake of 1.73% and phosphorus uptake of 12%. While Tilapia fish introduced into CW system units has the average weight of 60 g per fish.

Based on the results of this study, the simulation model was developed by using thermodynamic concept which is called emergy. Emergy evaluation tables were used to investigate the treatment performance of the constructed wetland system and then they were established to compare the production efficiencies and treatment efficiencies. The results showed that plant production efficiency was highest in Run 1 (OLR 10 kg BOD/ha-d) about 6.55%. In addition, fish production efficiency was highest in Run 2 (16 kg BOD/ha-d) with abundant energy transfer about 70%. Finally, to consider the main purpose of CW treatment, the emergy waste removal efficiencies were established to investigate treatment performance. Experimental Run 4 (63 kg BOD/ha-d) was found to contain highest emergy used in all parameters because it embodied more energy to produce wastewater than other loading rates. This thermodynamic model can be applied to use with other units by changing fish species or/and plant species or/and wastewater type or/and wastewater concentrations to help further optimizing the design of wastewater treatment system.

School of Environmental Engineering Student's Signature__________________

Academic Year 2008 Advisor's Signature __________________

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SYMBOLS AND ABBREVIATIONS

A	Area, m^2
C	Plant biomass
d_n	Depth of the wetland soil, m
d_w	Water depth, m
ε	Wetland porosity
E	The available energy or mass
F	Fish biomass
ha	Hectare
J_{R1}	Remainder sun available
J_N	Nitrogen inflow
J_P	Phosphorus inflow
J_{OM}	Organic matter inflow
J_1	Plant consumed by fish
J_2	Water used by plant
J_3	Nitrogen uptake by plant
J_4	Phosphorus uptake by plant
J_5	Organic matter consumed by fish
J_6	Treated wastewater
J_7	Nitrogen outflow
J_8	Phosphorus outflow
J_9	Organic matter outflow

SYMBOLS AND ABBREVIATIONS (Continued)

J_{10}	Sunlight received by plant
L	Length of the wetland, m
M	Emergy
n	Porosity
Q	Flowrate, m^3/d
S	Sun over specific area
t	Hydraulic retention time, d
Tr	Transformity
W	Width of the wetland, m
W_S	Water storage
W_W	Wastewater inflow
WW	Wastewater
V	Volume of waste stabilization pond, m^3
B	Boron
Bec	Base emergy change
BOD	Biochemical oxygen demand
$CaCO_3$	Calcium carbonate
Cl	Chloride
$C_6H_{12}O_6$	Glucose
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CW	Constructed wetland

SYMBOLS AND ABBREVIATIONS (Continued)

DO	Dissolved oxygen
EWRE	Emergy waste removal efficiency
FWS	Free water surface
GNP	Gross national product
HNO_3	Nitric acid
HRT	Hydraulic retention time
H_2O	Water
K	Potassium
N	Nitrogen
Na	Sodium
NH_3-N	Ammonia nitrogen
NO_3^-N	Nitrate nitrogen
NOD	Nitrogen oxygen demand
Np	Net profit
OLR	Organic loading rate
OM	Organic matter
o-PO_4^{3-}	Orthophosphate
O_2	Oxygen
P	Phosphorus
Pb	Lead
PO_4	Phosphate
Q_{avg}	Average flowrate

SYMBOLS AND ABBREVIATIONS (Continued)

Q_i	Input wastewater flowrate
Q_o	Output wastewater flowrate
q	Inlet hydraulic loading rate
sej	Solar emergy joules
SF	Subsurface
SO_4	Sulfate
SS	Suspended solid
SUT	Suranaree University of Technology
t	Hydraulic detention time, d
TKN	Total kjeldahl nitrogen
TN	Total nitrogen
TRP	Total reactive phosphorus
TP	Total phosphorus
TSS	Total suspended solid
UV	Ultraviolet
WSP	Waste stabilization pond

CHAPTER I

INTRODUCTION

1.1 Statement of the problem

Water pollution is becoming a serious issue of the entire world due to the rapid population growth, unsuitable treatment technology and inadequate management especially in small towns of Thailand. Lots of industries, services, and many human activities are packed within the communities and they are much denser than the past. Therefore, these activities release a large quantity of wastewater from many sources such as households, industries, restaurants, septic tanks which are discharged into water bodies without prior and proper treatment. They have made water pollution of which the average concentrations for biochemical oxygen demand (BOD), chemical oxygen demand (COD), etc. are higher than the standard level. In general, the main source of water pollution is the wastewater from domestic area that is about 80% of total wastewater. The major components of domestic wastewater are organic matter, nutrients and suspended solids (Seni Karnchanawong and Jaras Sanjitt, 1995). It is represented by the BOD values ranging from 100 to 400 mg/L (Kriangsak Udomsinroj, 1993). Thus, the wastewater should be properly treated before being discharged into water bodies.

There are several sophisticated treatment systems available, such as activated sludge process, rotating biological contactor, and aerated lagoon, but they require high capital, operational, and maintenance costs. Accordingly, biological treatment system with low operational and capital costs is preferred especially in small towns and, with a warm or hot climate all year round, Thailand has sufficient land for natural wastewater treatment technology. Thus, the maximum advantages of climate and land availability should be taken for wastewater treatment purpose. The attractive methods are waste stabilization pond (WSP) and constructed wetland (CW). These methods have been used as the effective low-cost technologies that require minimum energy to operate that are suitable for rural areas in Thailand. Facultative pond and free water surface wetland, both have been used to treat for secondary or tertiary treatment and sometimes can be applied to use in the same condition. Thus, the comparison of treatment efficiency for low-strength wastewater between WSP and CW was investigated to determine the optimum performance for further applications. In case of the treatment efficiency of both systems is similarly, CW has more value-added from plant production which is the benefit that can be gain from the system. However, many earlier studies on CW have been done by focusing on the advantages of plant and their usefulness for improving the effluent wastewater. Macrophytes play the dominant function to remove nutrients and organic matter in CW (Alvarez and Becares, 2008). Similarly, in natural ecosystem, consumers in upper trophic level as generally as fish, occur in the system. But few studies related to CW and WSP, have been evaluated about fish production and the effect of wastewater treatment from fish. Fish use producers as a shelter, an either food source, spawning, nesting and nursery sites. Moreover, algae and submerged part plant usually exist in the biological treatment systems, lead to raise BOD and suspended solids (SS) contents of the effluent, are consumed by fish. Finally, fish contains high protein and it is easily harvestable for other uses such as animal feed in waste recycling point of view

(Chongrak Polprasert, 1996). Thus, fish will be a value added of the systems apart from the treatment concept.

The CW with fish in the system involves a food chain in the ecosystem. The treatment performance and the advantages in CW influence by the efficiency of energy transfer in the ecosystem. Therefore, energy transfer should be taken into account to evaluate the treatment performance in a system unit. The energy contained in the aquatic plant and algal cells present in CW are ultimately derived from sunlight through photosynthesis. These are basically the activities of capturing solar energy and converting them into the biomass. Furthermore, algal cells and submergent plant were consumed by fish which is the next level in the food chain as same as in ecosystem. Therefore, it would be appropriate to describe the relationship among fish, aquatic plant and wastewater in CW with a thermodynamic model.

In this study, the potential of aquatic plant to remove pollutants from wastewater and produce useful crop was demonstrated. Fish production in treatment wetlands was an interesting research area to explore the possibility to rear fish using domestic wastewater. Finally, thermodynamic model in CW was developed to estimate the potential of treatment system.

1.2 Objectives of the study

The principal objectives of this study are:

1. To determine the organic and nutrient removal efficiencies in free water surface treatment wetlands using aquatic plant and fish.

2. To investigate the biomass productivity of fish and aquatic plant grown in treatment wetlands.

3. To establish thermodynamic model that can describe water quality, macrophyte and fish present in the systems.

1.3 Scopes of the study

The pilot-scale treatment systems were designed and constructed to treat wastewater from the dormitories of Suranaree University of Technology (SUT). This wastewater was discharged into four compartments:

a) Waste stabilization pond;

b) Waste stabilization pond with fish (*Oreochromis niloticus* L.);

c) Constructed wetland with Cyperus papyrus (*Cyperus papyrus* Linn.); and

d) Constructed wetland with Cyperus papyrus and fish.

Tilapia was introduced into the above-mentioned ponds and *Cyperus papyrus* Linn. was planted in the constructed wetland units. In this study, waste recovery and wastewater treatment were focused over different treatment systems.

Treatment efficiencies of these systems were determined with respect to the reduction in quantities of BOD, COD, total suspended solids (TSS), nitrogen and phosphorus in the wastewater effluents. The plant's height was measured every 10 days, lasting two months long. In addition, the plant was cut at the end of the experiment and brought to determine the biomass, plant productivity and the nutrients uptake by plants. Tilapia was also weighed every 15 days to estimate fish production. Finally, the results of plant and fish production, and the influent and effluent wastewater concentrations were utilized to establish the appropriate energy model of wetland for Thailand as a case study.

CHAPTER II

LITERATURE REVIEW

Advance techniques to improve water quality, reuse and recycling require high technology with highly expensive capital and operational costs. In this circumstance, it has been widely attractive to apply the constructed wetlands (CW) to treat wastewater. Current applications of CW technology include the treatment of primary settled, secondary treated sewage, tertiary effluent polishing, disinfection, urban and rural runoff effluent treatment (nutrient assimilation, and nutrient removal via biomass production and export), and groundwater recharge (Bavor, Roser, and Adcock, 1995). Wetlands are ecosystems that occur in areas that are intermediate between uplands and deep-water aquatic systems. They consist of saturated soil, shallow water condition and colonization by adapted aquatic plant and animal communities (Kadlec and Knight, 1996).

In general, wetlands are classified into two types-natural and constructed wetlands. CW can be defined into two systems characterized by the flow path of the water in the systems. The first is called free water surface wetlands (FWS) that surface of water is exposed to the atmosphere as it flows through the bed. The second is called subsurface wetlands (SF) that the water level in the bed is maintained below the top of the media. The SF systems have the major advantage of minimizing vector and odor problems, greater cold tolerance, and possible higher treatment efficiency per unit land area for some major pollutants due to greater surface area for microbial activity. The advantages of the FWS systems are in their lower capital and operating costs which position them as the favored ones at locations where land cost is not a constraint and winter temperatures are not severe. They may have less clogging problems compared to SF systems (Poh–Eng and Chongrak Polprasert, 1996).

2.1 Free water surface wetland

In general, FWS systems consist of basins or channels, with some barrier to prevent seepage, soil or another suitable medium to support the macrophyte, and water at a relatively shallow depth flowing through the unit (Figure 2.1). The shallow water depth, low flow velocity, and presence of the plant stalks regulate water flow and, especially in long, narrow channels, ensure plug-flow conditions (Reed, Middlebrooks, and Crites, 1988).

FWS have some properties in common with facultative lagoons and also have some important structural and functional differences. Main process of FWS treatment wetlands is biological process. Inflow water containing particulate and dissolved pollutants slows and spreads through a large area of shallow water and aquatic plants. These insoluble pollutants enter into the biogeochemical element cycles within the water column and surface soils of the wetland. At the same time, a fraction of the dissolved BOD, total nitrogen (TN), total phosphorus (TP) and trace elements are sorbed by soils and active microbial and plant populations throughout the wetland environment. These dissolved elements also enter the overall mineral cycles of the wetland ecosystem (Kadlec and Knight, 1996).

Settleable organics are rapidly removed in FWS wetlands by latent conditions, deposition, and filtration since attached and suspended microbial growth is responsible for removal of soluble BOD. The major oxygen source for these reactions

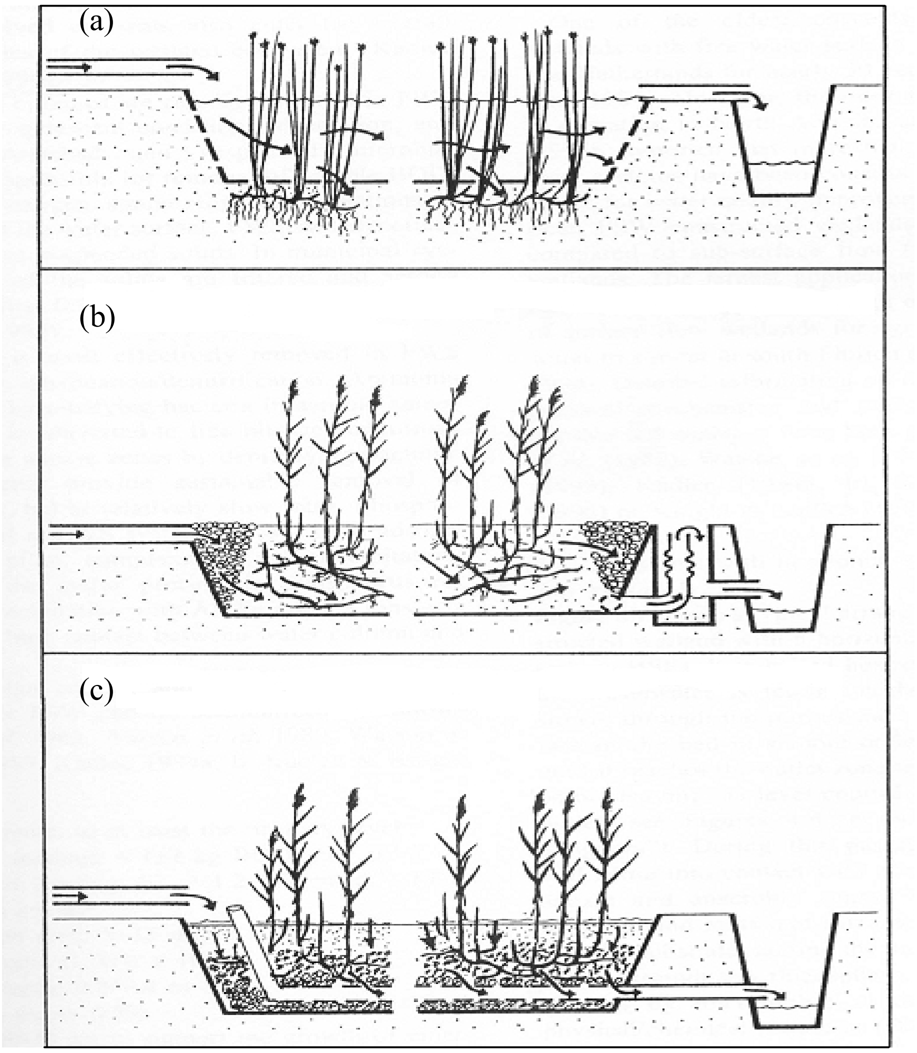


Figure 2.1 Schematic representation types of constructed wetland (Brix, 1993) (a) Emergent macrophyte treatment system with free water surface flow (b) Emergent macrophyte treatment system with horizontal subsurface flow (c) Emergent macrophyte treatment system with vertical subsurface flow (percolation).

is reaeration at the water surface. Accordingly, FWS systems effectively remove SS. Specially, in municipal wastewater treatment systems, most of the solids are filtered and settled within the first few meters beyond the inlet (Watson et al., 1989).

Nitrogen is most effectively removed in FWS systems by nitrification and/or denitrification. Moreover, it is also taken up by plants, incorporated into the biomass and released back as organic nitrogen after decomposition. FWS systems provide sustainable removal of phosphorus even though at relatively slow rates. Phosphorus removal in FWS systems, occurs from adsorption, absorption, complexation and precipitation.

Pichittra Chayopathum (2001) conducted two CW by utilizing sedges and cattails to treat swine wastewater. The removal efficiencies were found to be in ranged of 66-92% for BOD, 70-97% for TSS, 72-96% for TKN, 47-83% for NO_3^--N, 39-81% for TP, and 52-85% for Total Coliform Bacteria. Similary, (Sajn Slak, Bulc and Vrhovsek, 2005) studied the treatment performances between FWS and WSP. They reported that pilot FWS planted with *Phragmites australis* and *Eichhornia crassipes* proved more efficient in decreasing the SS (64.6%), settleable solids (91.8%), organic N (59.3%), TN (38%), COD (67.2%) and BOD (72.1%) that were higher than the WSP.

2.2 Wetland processes

2.2.1 Wetland hydraulics

Wetland hydraulics is the term applied to the movement of water through the wetland. Improper hydraulic design can cause problems with water conveyance, water quality, odors, and vectors.

2.2.1.1 Wetland hydraulic definitions

Wetland porosity or void fraction: In a natural or CW, the vegetation occupies a portion of the water column, thereby reducing the space available for water. The porosity of the wetland (ε), or void fraction, is the ratio of the theoretical or empty basin volume to the actual volume available for water to occupy in a wetland.

The overall effect of porosity is to reduce the wetland volume available for water flow and storage. On the other hand, this reduction in volume reduces the amount of time water remains in the wetland, and the potential for constituent removal to occur. Lower wetland porosity values correspond to a lower fraction of the wetland volume available for water, shorter hydraulic detention times, lower removal efficiencies, and result in larger required wetland areas to achieve desired treatment goals. To be conservative, a porosity (ε) value of 0.7 to 0.9 could be used in FWS constructed wetland design calculations, with lower ε values for densely vegetated wetlands, and higher ε values for wetlands with more open water areas.

Hydraulic detention time: in a constructed wetland system, the hydraulic retention time (HRT) is one of the major factors affecting the treatment performance. In general, very long HRT can be significant as anaerobic conditions whereas shorter HRT do not provide sufficient time for the degration of pollutants (Poh–Eng and Chongrak Polprasert, 1996). The theoretical hydraulic detention time can be calculated as:

$$t = \frac{V\varepsilon}{Q} \tag{2.1}$$

Where:

t = hydraulic detention time, (t)

V = volume of wetland basin, (L^3)

ε = wetland porosity, and

Q = flowrate, (L^3/t)

Hydraulic loading rate: the hydraulic loading rate (q) is also known as surface hydraulic loading rate refers to the volume of wastewater applied to the system per unit surface area per day. The hydraulic loading rate is defined as:

$$q = \frac{Q}{A} \qquad (2.2)$$

Where:

q = inlet hydraulic loading rate, (L/t)

Q = flowrate, (L^3/t)

A = wetland surface area, (L^2)

2.2.2 Wetland Biogeochemistry

FWS treatment wetlands support a variety of sequential and often complementary treatment processes. The predominant physical, chemical, and biological mechanisms operative in FWS treatment wetlands are summarized in Table 2.1. These interrelated biological, chemical, and physical treatment processes control the transport and transformation of constituents through FWS wetlands. A hypothetical partitioning of treatment processes throughout the wetland volume is shown in Figure 2.2 (Stowell et al., 1981).

Table 2.1 Mechanisms and factors that affect the potential for removal or addition of water quality constituents in FWS wetlands. (Stowell et al., 1981).

Mechanism	Water Quality Constituent*							Description
	BOD	SS	N	P	DO	Bacteria Virus	Heavy Metal	
Physical								
Absorption			S		P/S			Gas transfer to and from water surface
Adsorption/ desorption	I	S				P	I	Interparticle attractive force (van de Waals force); hydrophilic interaction
Emulsification		S					S	Suspension of low solubility chemicals
Evaporation						I	S	Volatilization and aerosol formation; thermal moderation
Filtration Impaction	I	S					I	Particulates filtered mechanically as water passes through substrate and plants
Flocculation	P	P				P	S	Interparticle attractive force (van de Waals force); hydrophilic interaction
Photochemical reactions								Solar radiation is known to trigger a number of chemical reactions. Radiation in the near-ultraviolet (UV) and visible range is known to cause the breakdown of a variety of organic compound. Pathogenic bacteria and virus attenuation.

Table 2.1 Mechanisms and factors that affect the potential for removal or addition of water quality constituents in FWS wetlands (continued).

Mechanism	Water Quality Constituent*							Description
	BOD	SS	N	P	DO	Bacteria Virus	Heavy Metal	
Sedimentation	P	P	I	I	I	S	P	Gravitational settling of larger particles and contaminats
Thermal	I		P	S				Autoflocculation; natural coagulants
Sedimentation	P	P	I	I	I	S	P	Gravitational settling of larger particles and contaminats
Volatilization			P					Similar process to gas absorption, except that the net flux is out of the water surface
Chemical Adsorption				P		S	S	On substrate and plate surfaces
Chelation				S			P	Formation of complex metal compounds through ligands
Chemical reactions								Hydrolysis, for example, is an important chemical reaction that occurs in the environment, by which proteins are converted into amino acids and other soluble compounds.
Chemical Decomposition						P		Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation. hydrolysis

Table 2.1 Mechanisms and factors that affect the potential for removal or addition of water quality constituents in FWS wetlands (continued).

Mechanism	Water Quality Constituent*							Description
	BOD	SS	N	P	DO	Bacteria Virus	Heavy Metal	
Oxidation/ reduction reactions	P	S					P	Anoxic condition; metal speciation; organic acid production
Precipitation				P			P	Formation of co-precipitates with insoluble compounds
Oxidation/ reduction reactions	P	S					P	Anoxic condition; metal speciation; organic acid production
Biological Algal synthesis			S	S				The synthesis of algal cell tissue using the nutrients in wastewater.
Assimilation, plant	C	C	S	P/ S	I/C	I	S	Uptake and metabolism by plant; root excretions may be toxic to enteric organisms; transpiration concentrates effluents; dissolved oxygen supply
Bacteria/ Metabolism								Removal of colloidal solids and soluble organics by suspended, benthic and plant supported bacteria; bacterial nitrification, denitrification; microbial mediated oxidation

Table 2.1 Mechanisms and factors that affect the potential for removal or addition of water quality constituents in FWS wetlands (continued).

Mechanism	Water Quality Constituent*							Description
	BOD	SS	N	P	DO	Bacteria Virus	Heavy Metal	
Aerobic	P/C	S	I	I	P	P		
Anaerobic		P/C	C	C				
Plant adsorption			S	S	C		S	Under proper conditions, significant quantities of contaminants will be taken up by plants.
Predation		P				S		Zooplankton and aquatic insect larva particles; odonata and fish-aquatic insect

Note: *P = primary processes, S = secondary processes, I = incidental effect (occurring with removal of other constituent), C = contributory effect, S/P = depends on influent and design conditions, N = negative.

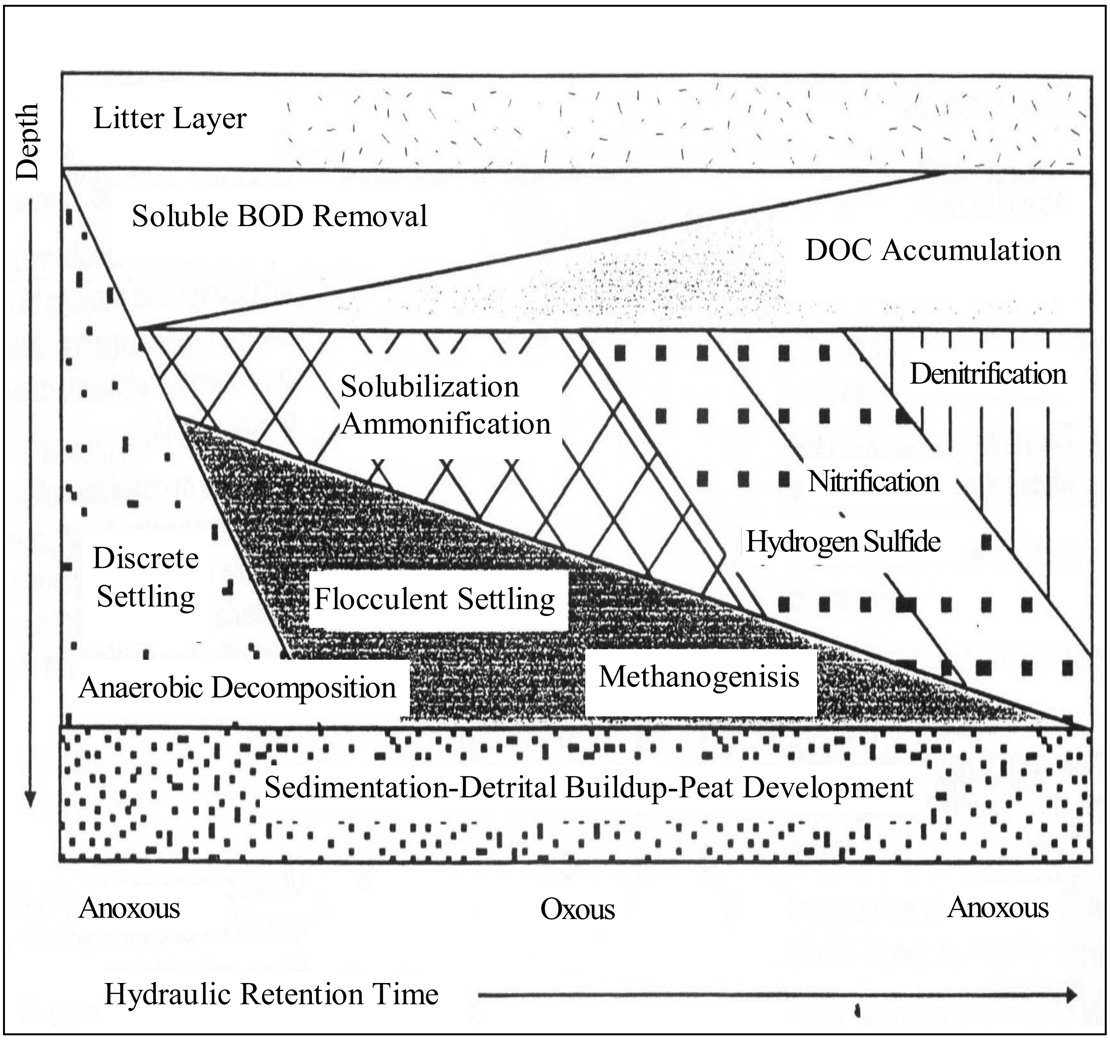


Figure 2.2 Conceptual partitioning of treatment processes through a FWS wetland (Stowell et al., 1981).

This brief introduction illustrates how FWS wetlands incorporate a similar sequence of physical, chemical, and biological treatment processes to those commonly employed in conventional wastewater treatment. FWS wetlands can be designed to emphasize some treatment processes over others by altering the geometry, hydraulics, and plant types, densities, or locations.

1) Total suspended solids

Total suspended solids (TSS) are both removed and produced by natural wetland processes. During treatment, settleable incoming particulate matter usually has long time to settle and become trapped in litter or dead zones. Soluble organic components are reduced to carbon dioxide and low molecular weight organic acids and inorganic constituents can become bound as sulfide complexes or become buried through sediment accretion.

Wetland scientists generally refer to the combination of removal processes as filtration, although stem and litter densities are not typically high enough to act as a filter mat. As shown in Figure 2.3, a number of wetland processes produce particulate matter including: death of invertebrates, fragmentation of detritus from plants and algae, and formation of chemical precipitates such as iron sulfide. Bacteria and fungi can colonize these materials and add to their mass.

The suspended solids (nonfilterable residue) content of wastewater is of direct water quality significance in terms of turbidity in receiving waters, and indirectly in relation to the associated transport of other waste constituents such as nitrogen, phosphorus, and BOD (Poh–Eng and Chongrak Polprasert, 1996).

Mann and Bavor (1993) conducted a large–scale investigation of constructed wetland systems for sewage effluent treatment. They suggested that 80-90% of both primary and secondary influent solids were volatile. In many systems, however, the majority of settleable solids are removed in a mechanical pre-treatment unit before the wastewater is discharged to the actual wetland system.

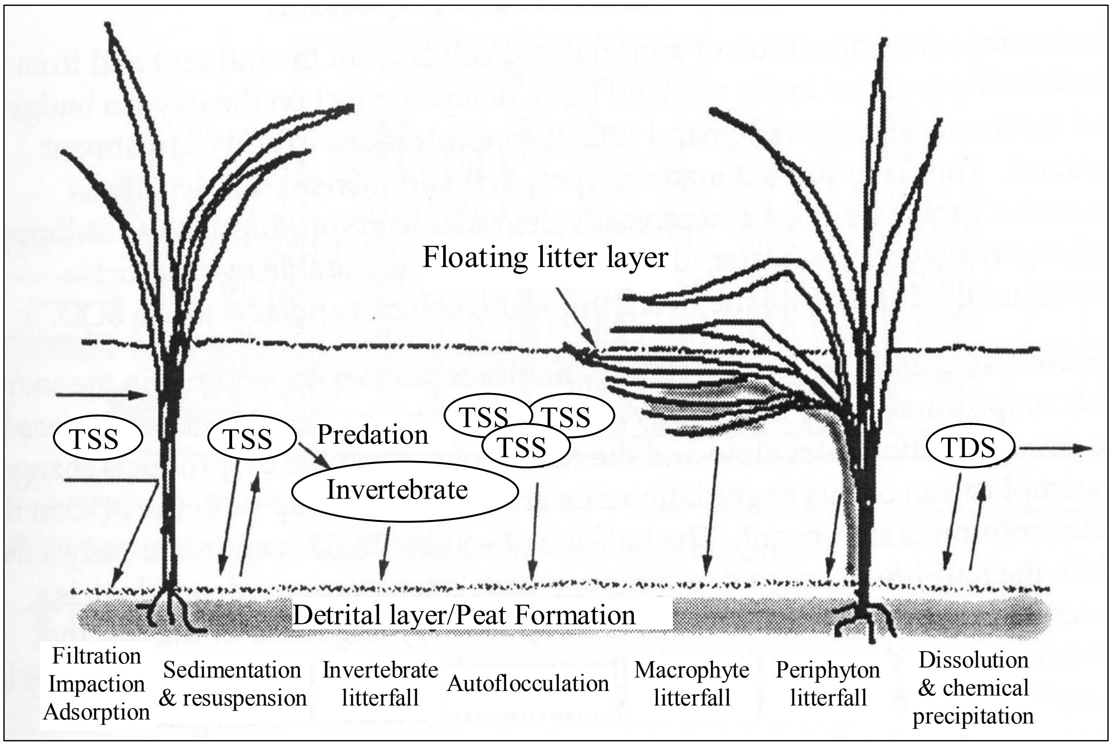


Figure 2.3 Wetland TSS removal, re-suspension, and internal generation processes (Kadlec and Knight, 1996).

Sajn Slak, Bulc, and Vrhovsek (2005) explained that FWS wetland had higher removal efficiency (64.6%) than WSP (31.6%). The higher mass removal rate in the FWS occurred because of sorption on the biofilm which develop on the surface of macrophytes and detritus. Moreover, the emergent macrophytes in FWS were shaded the sunlight from the water surface that causes the decreasing of algal mass in the system.

2) Biochemical oxygen demand

Particulate settling provides one removal mechanism, and typically occurs in the inlet region of the wetland (Figure 2.4). Microbial communities process the dissolved carbon compounds. Microbial removal processes include oxidation in

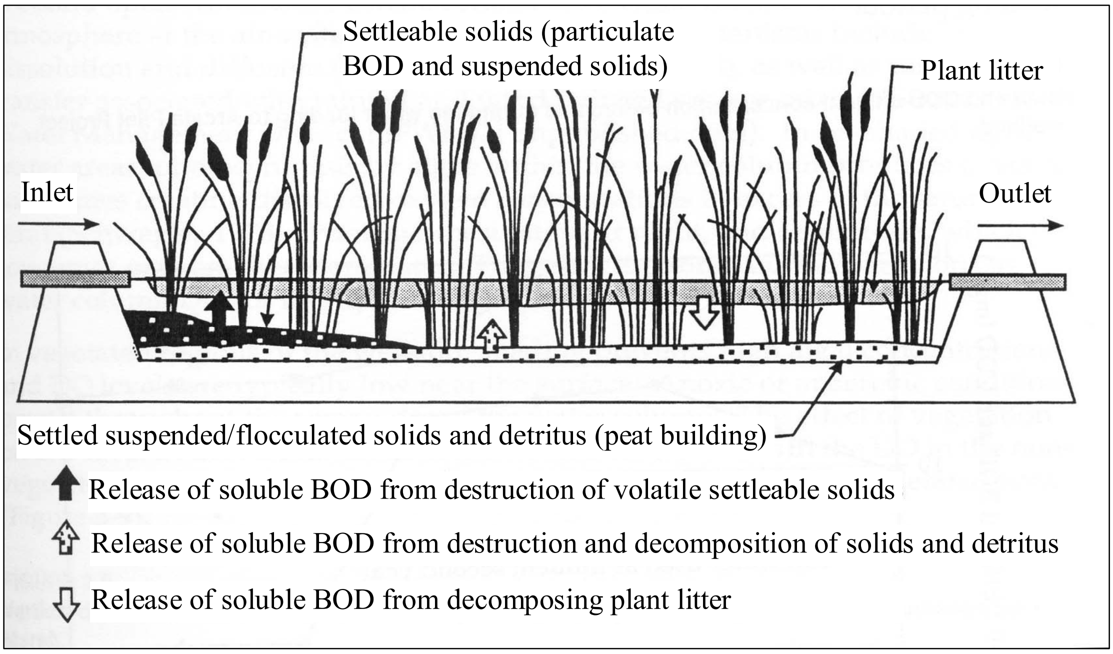


Figure 2.4 Simplified portrayal of wetland carbon processing (U.S. EPA, 2000).

the aerobic regions of the wetland and methanogenesis in the anaerobic regions. Active microorganisms are usually associated with solid surfaces.

In addition to microbial decomposition, dissolved carbon is fixed into new biomass during photosynthesis. The decomposition of this biomass, litter and sediments produces a return flux of BOD to the water column. The balance between removal of influent BOD and the decomposition processes contributing BOD determines the wetland effluent concentration of this constituent.

Gearheart (1992) revealed that the City of Arcata's pilot project, showed lower hydraulic loading rates produced higher BOD removal efficiencies. Seasonal variations in effluent concentration affected by vegetation type, density, and distribution.

3) Chemical oxygen demand

The chemical oxygen demand (COD) measures the concentration of oxidizable compounds using a strong chemical oxidant. Thus, the COD test measures the sum concentration of two distinct fractions of oxidizable compounds: easily biodegradable compounds and oxidizable but not easily biodegradable compounds. The concentration of easily biodegradable compounds is often represented as BOD_5, the BOD measured after 5 days of incubation, with the difference between the COD and BOD_5 representing the concentration of compounds that is not easily biodegradable. Some of these non-BOD compounds are degradable under anoxic conditions via anaerobic decomposition, or under aerobic conditions in periods of longer than 5 days.

4) Dissolved oxygen

Dissolved oxygen (DO) is depleted to meet wetland oxygen requirements in four major categories: sediment/litter oxygen demand, respiration requirements, dissolved carbonaceous BOD, and dissolved nitrogenous oxygen demand (NOD). Sediment oxygen demand is the result of decomposing detritus generated by carbon fixation in the wetland, and the decomposition of precipitated organic solids that entered with the wastewater. NOD is exerted primarily by NH_3-N, but ammonium may also be contributed by the mineralization of organic nitrogen. Decomposition processes in the wetland also contribute to NOD and BOD, further increasing the oxygen demand and reducing the DO in the wetland water.

Plant roots also require oxygen, which is normally transported downward through passages (aerenchyma) in stems and roots. Some surplus of oxygen may be released from small roots into their immediate environs, but it is quickly consumed by the local oxygen demand (Brix, 1994).

Wetland open-water areas can be aerated via oxygen transfer from the atmosphere at the air-water interface. Reaeration mechanisms include dissolution and diffusion as well as turbulent transfer associated with rainfall and wind induced surface mixing. In un-shaded open water areas, photosynthesis by algae within the water column produces oxygen, sometimes creating dissolved oxygen concentrations in excess of the saturation limit. Photosynthesis stops at night, and respiration, which consumes oxygen, then dominates. The result is strong diurnal variations in water column DO for lightly loaded, algae-rich, open water wetlands.

5) Nitrogen

Nitrogen is a key element in biogeochemical cycles and occurs in a number of different oxidation states in natural and constructed treatment wetlands. Numerous biological and physiochemical processes can transform nitrogen between its various oxidation states (Figure 2.5). The dominant nitrogen species entering a FWS treatment wetlands depends on the level and type of wastewater pretreatment, but may include organic, ammonia, nitrate, and nitrite nitrogen, and nitrogen gases (di-nitrogen gas (N_2) and di-nitrogen oxide (N_2O)).

NH_3-N can be oxidized in open, aerobic zones to nitrite and nitrate nitrogen through an aerobic microbial process called nitrification. NH_3-N may also be biologically assimilated and reduced back to organic nitrogen in the plants, or may be removed from the water column by adsorption to solid surfaces, such as wetland sediments. Adsorbed ammonium is readily released back to the dissolved ammonia state under anaerobic conditions. Wu, Franz, and Chen (2001) indicated that ammonia

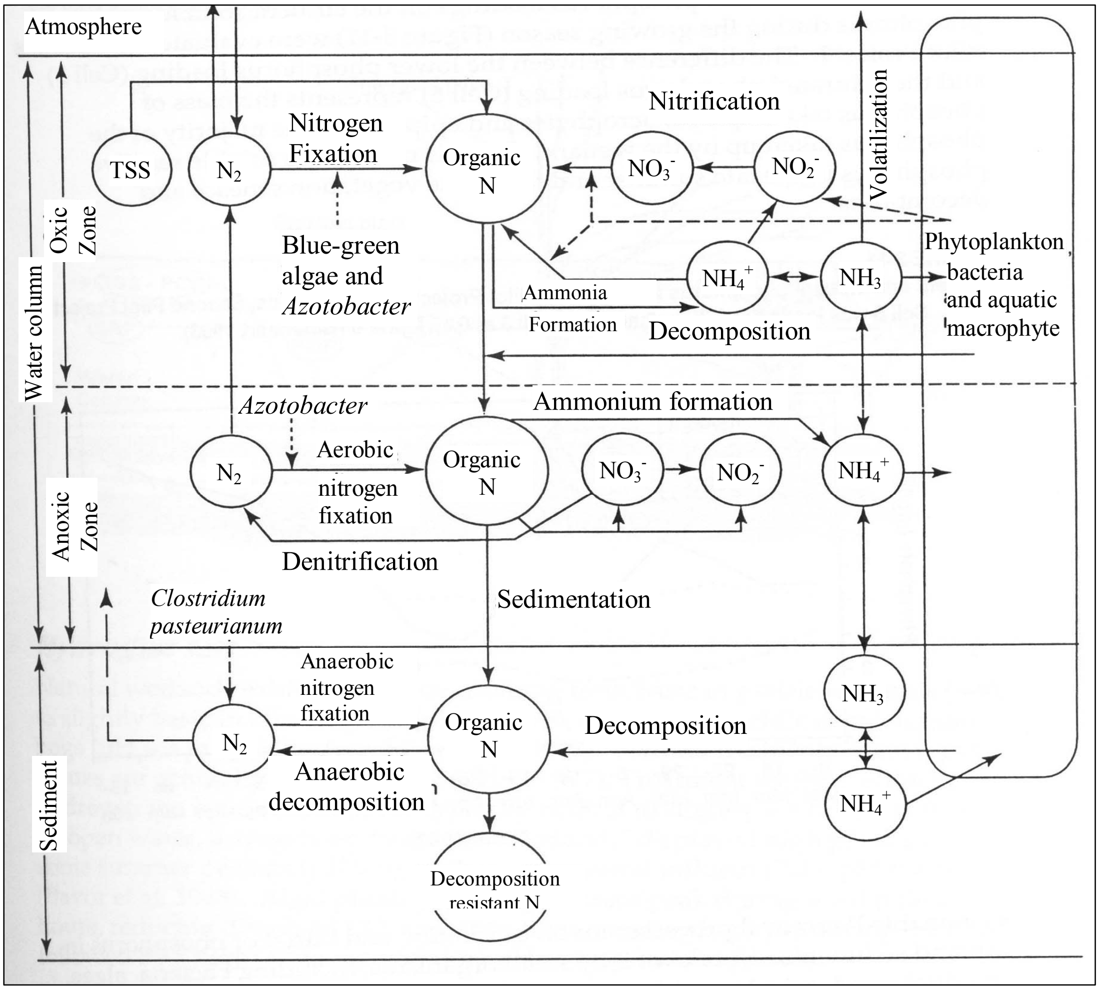


Figure 2.5 Nitrogen transformation processes in wetlands (U.S. EPA, 2000).

removal efficiency in CWs is often limited by the amount of oxygen available in the system.

Nitrate nitrogen is readily transformed to N_2 in treatment wetlands by the microbiologically mediated anaerobic process, denitrification. Denitrification occurs most readily in wetland sediments and in the water column below fully vegetated growth where DO concentrations are low and available organic carbon is high. Organic carbon is consumed in this microbial process and alkalinity is produced.

To complete the cycle, atmospheric N_2 can be fixed by autotrophic organisms in open zones as organic N. However, this transformation is not normally a significant contribution of organic N to FWS treatment wetlands. Because of the complex transformations affecting nitrogen species in wetlands, a sequential series of reactions must be considered to adequately describe treatment performance, even not the most elementary level.

In a research, the uptake of ^{15}N by macrophytes in subsurface flow wetlands treating domestic wastewater was studied. Two constructed subsurface flow wetlands were employed to determine the efficiency of different macrophytes in uptake of ^{15}N labeled ammonium sulfate. Macrophytes in Wetland 1 recovered 35% of the added N in their shoots but only 5% of the added N was recovered in the shoots and roots in Wetland 2. A major difference for the two wetlands was N and hydraulic loading. Wetland 1 received 7.5 Kg N/ ha-d and Wetland 2 received 16.9 Kg N/ ha-d. Retention time for Wetland 1 based on pore volumes was 2.9 d and for Wetland 2 it was 1.2 d. The retardation factor for NH_4^+ was approximately 2.5 for both wetlands and breakthrough curves indicated lack of plug flow. The importance of macrophytes in taking up NH_4^+ appeared to dependent on N and hydraulic loading (Weaver, Lane, Johns and Lesikar, 2001).

Van Oostrom (1995) studied the effect of plant and influent organic matter on nitrogen removal in four experimental surface flow wetlands treating a nitrified meat processing effluent. Three wetlands contained a floating mat of the plant *Glyceria maxima*. The fourth contained a simulated plant mat constructed of nylon fabric. The influent of 50% recycle was irrigated over two of the plant containing wetlands, while the other wetlands received influent at one end as per normal practice. Nitrogen removal in the planted wetlands during the final year of the study was about twice that in the wetland without plants, and averaged 46-49% (5.2-5.5 g N/m^2-d) at a high average loading rate of 11.2 g N/m^2-d. Summertime nitrogen removal reached 75%. About 87% of the nitrogen removed by the planted wetlands was due to denitrificaiton, with 13% due to accumulation in sediment and plant biomass. The plants and influent organic matter were each responsible for about 50% of nitrogen removal, mainly through supplying organic carbon and creating anaerobic conditions for denitrification. Irrigation of wastewater over the plant mat did not enhance nitrogen removal.

6) Phosphorus

New constructed and natural wetlands are capable of adsorpting and absorbing phosphorus (P) loading until the capacity of the soils and new plant growth are saturated. The potential for P removal is most easily illustrated by the seasonal uptake and release by plants of soluble reactive phosphorus.

Sustainable P removal processes involve accretion and burial of phosphorus in wetland sediments. Uptake of P by small organisms act as a rapid-action, partly reversible removal mechanism (Figure 2.6). Cycling through growth, death, and decomposition returns most of the microbiotic uptake back to the water column, but a significant residual is lost to long-term accretion in newly formed sediments and soils. Direct settling and trapping of particulate P may also contribute to the accretion process.

7) Organic compounds

Settleable organics are rapidly removed in wetland systems under quiescent conditions by deposition and filtration. Attached and suspended microbial

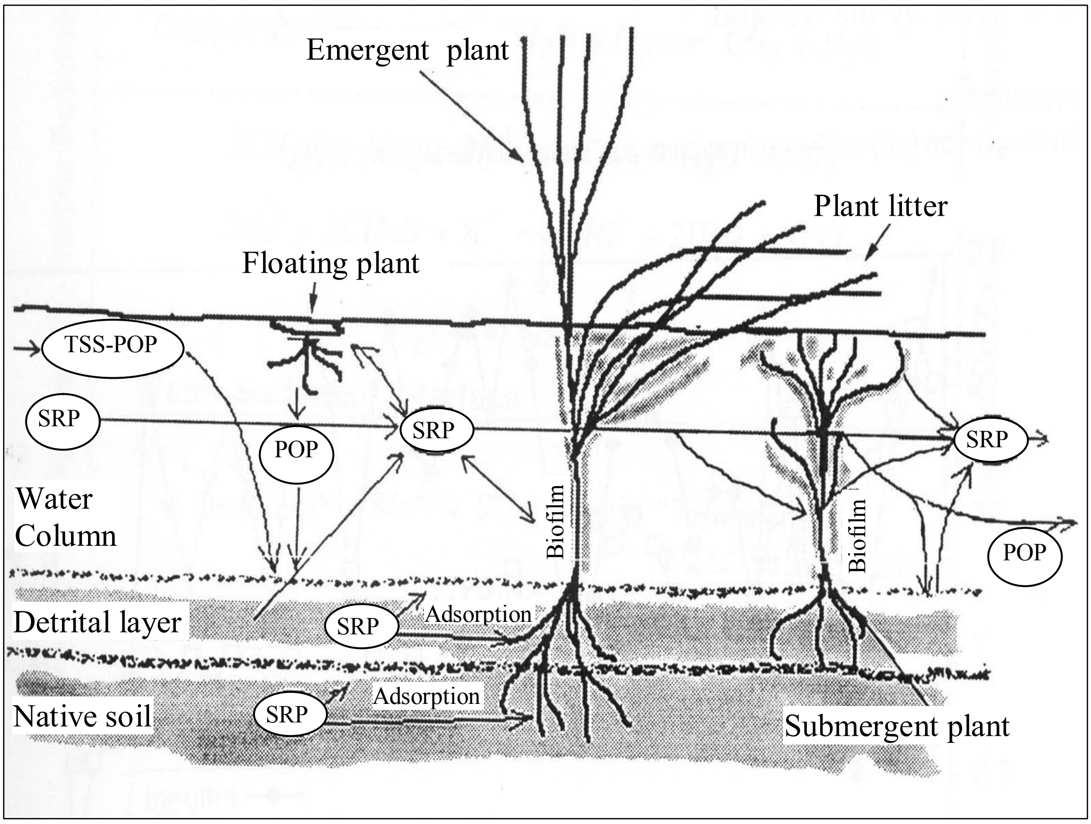


Figure 2.6 Conceptual cycling of phosphorus forms in FWS constructed wetlands SRP: Soluble reactive phosphorus; POP: particulate organic phosphorus; TSS-POP: form of POP in terms of a fraction of the total suspended solids (U.S. EAP, 2000).

growth is responsible for removal of soluble organics. Organic compounds are degraded aerobically as well as anaerobically. The oxygen required for aerobic degradation is supplied directly from the atmosphere by diffusion or oxygen leakage from the macrophyte roots into the rhizosphere. Uptake of organic matter by the macrophyte is negligible compared to biological degradation (Watson et al., 1989; Cooper et al., 1996).

Chongrak Polprasert, Nawaraj Khatiwada, and Bhurtel (1998) reported a model for organic matter removal in FWS constructed wetlands. This study demonstrated the significance of the biofilm bacteria present in the FWS constructed wetland unit in biodegrading organic matter, while the suspended bacteria activity was found to be insignificant. A kinetic model incorporating the activity of the biofilm bacteria and dispersion number is proposed for calculating COD removal efficiency in FWS constructed wetlands.

8) Pathogens

Bacteria and viruses are important organisms from a public health point of view but protozoan pathogens and helminthic worms are also of particular importance in tropical and subtropical countries. CWs are known to offer a suitable combination of physical, chemical and biological factors for the removal of pathogenic organisms. Physical factors include mechanical filtration and sedimentation. Chemical factors include oxidation, UV radiation, exposure to biocides excreted by some plants and adsorption to organic matter. Biological removal mechanisms include antibiosis, predation by nematodes, protests and zooplankton, attack by lytic bacteria and viruses and natural die-off.

2.3 Design Criteria

The principal process variables for CW systems include organic loading rate (OLR), hydraulic loading rate (HLR), hydraulic retention time (HRT) and water depth (for FWS systems only). Recommended ranges for design are given in Table 2.2.

Table 2.2 Summary of design guidelines for free water surface constructed wetland.

Design parameter	Unit	Type of system FWS	Source
Organic loading rate (as BOD loading rate)	kg/ha.day	<110 <112 100-110 <67 <80 <100	Reed et al. (1988) US. EPA (1988) WPCF (1990) Tchobanoglous and Burton (1991) Crites (1994) Reed and Brown (1995)
Hydraulic loading rate	cm/day	2.5-5 1.4-4.7 0.7-6	WPCF (1990) Tchobanoglous and Burton (1991) Crites (1994)
Hydraulic retention time	days	5-10 4-15 5-14	WPCF (1990) Tchobanoglous and Burton (1991) Crites (1994)
Water depth	m	<0.5 0.09-0.6 0.1-0.5	WPCF (1990) Tchobanoglous and Burton (1991) Crites (1994)

Source: Modified from Poh–Eng and Chongrak Polprasert (1996).

2.4 Wetland animals

Animals frequently focus and control energy flows in wetland ecosystems. Artificial wetlands receiving sewage effluent provide permanent wildlife habitats and improve the landscape amenity (Greenway and Simpson, 1996). The commonly animal in the natural wetlands is fish.

Fish can be classified into three groups on the basis of their feeding habits: herbivorous fish, carnivorous fish, and omnivorous fish. In this study, tilapia is classified into omnivorous fish group which is selected to rear in the treatment systems. Tilapia are native to Africa, but have been introduced in many countries around the world. They are disease resistant, reproduce easily, eat a wide variety of foods and tolerate poor water quality with low dissolved oxygen levels. Most will grow in brackish water and some will adapt to full strength sea water. These characteristics make tilapia suitable for culture in most developing countries (International Center for Aquaculture and Aquatic Environments Auburn University, www, 2002).

Tilapia is an omnivorous fish which consumes both animals and plants (Chongrak Polprasert, 1996). Fish to be reared in waste-fed ponds should have the following characteristics:

- Tolerant to low DO level which can occur during the night of at dawn when photosynthetic oxygen production does not occur;
- Herbivorous or omnivorous in nature to feed on the waste-grown phytoplankton; and
- Tolerant to disease and other adverse environmental conditions.

Chongrak Polprasert (1996) summarized that some fish species, such as tilapia, Chinese carp, and Indian carp have been used in waste recycling practices. Organic wastes, including feacal sludge, could provide sufficient nutrients to promote the growth of phytoplankton, and consequently of zooplankton, which are the natural food of these fish. Among these species, tilapia needs to be particularly mentioned, because it is used in waste recycling in tropical and subtropical areas. It feeds directly on algae and other primary aquatic vegetation (and on zooplankton as well). It grows rapidly and multiplies abundantly. Furthermore, it has better tolerance to low DO level and resistance to diseases (which often occur in fish ponds) than many other species such as carp.

Moreover, some studies introduced fish in rice fields. Rice fields are temporary man-made aquatic habitats. They are planted and harvested once or twice a year and cover a range of irrigated, rainfed, tidal wetland, and deepwater environments. The common carp, *Cyprinus carpio* (Cyprinidae), and the Nile tilapia, *Oreochromis niloticus* (Cichlidae), both have been successfully cultured in rice fields in the Asian region and therefore have been recommended for culture in Philippine rice fields as well (Halwart, 1994).

2.5 Aquatic plant

Emergent macrophytes have large internal air spaces for transportation of oxygen to roots and rhizomes (Brix, 1987). The plant rhizome provides surface for bacterial growth as well as for filtration of solids. More importantly, plants are known to translocate oxygen from the shoots to the roots (Chongrak Polprasert, 1996).

Emergent aquatic macrophytes are the dominating life form in wetlands, growing within a water-table range 50 cm below the soil surface to a water depth 150 cm or more. In general they produce aerial stems and leaves and an extensive root and rhizome system.

Guntenspergen, Stearns, and Kadlec (1989) pointed out that the vegetation in wastewater act as a temporary storage pool, with most pollutant transformations and sequestering processes occurring in the substrate. Emergent and floating leaved species were preferentially used in pilot studies of CW. Submerged aquatic plants do not appear to have attributes that would be useful in wastewater treatment. They have low production rates and many species are intolerant of eutrophic conditions and have detrimental interactions with algae in the water column.

Furthermore, Greenway (1997) reported the nutrient content of wetland plants in CW receiving municipal effluent in tropical Australia. Several pilot wetlands were constructed in Queensland to treat municipal wastewater. The result showed that most species translocated to the CWs flourished indicating their ability to tolerate nutrient enriched waters, and tended to have higher tissue nutrient concentrations than their controls in natural wetlands. Pooled data showed no significant difference between tissue nutrient content in plant components, though nitrogen was highest in the leaves and phosphorus highest in the roots of most species.

Like any other plants, aquatic plants require nutrients and light. The major factors governing their growth are:

- ambient temperature
- light
- nutrients and substrate in the water

- pH of water
- dissolved gases present in the water
- salinity of the water
- toxic chemicals present in the water substrate and turbulence
- water current in rivers and lakes
- river floods
- morphology of water bodies.

While these factors modify the composition of the plant communities, they are in turn modified by the latter (Polprasert, 1996).

2.5.1 Nutrient uptake

Aquatic macrophyte uptake nutrients with root systems. The amounts of nutrient uptake are considered from the plant biomass. The uptake rate of a plant is limited by a net growth rate and the concentration of nutrients in the plant tissue. Vegetation nutrient concentrations tend to be highest early in the growing season, and then decreasing as the plant mature.

2.5.1.1 Nitrogen

Nitrogen assimilation is the processes that convert inorganic nitrogen forms into organic compounds which the two forms of nitrogen generally used for taking up are ammonia and nitrate nitrogen. The amount of treatment of nitrogen by CW is also dependent on the amount of time that the wastewater remains within the system and the ability of rooted macrophyte to utilize nutrients may partially account for their greater productivity (Vymazal, 2005). Most of the biomass release nitrogen into many parts of wetland such as wetland water, dead plant material and litter, and rhizome. Thus, the movement of nitrogen through the vegetation results in the enhancement of processes other than in soil, water column and the associated biofilms (Kadlec and Knight, 1996). Besides the macrophyte growth is not the only potential biological nutrient uptake process: microorganisms and algae also utilize nitrogen in wetlands. Several researchers reported the aboveground N standing stock values which were in the range of 0.6-88 g N/m^2 (Vymazal, 2007).

2.5.1.2 Phosphorus

Phosphorus uptake by macrophytes is usually highest during the beginning of the growing season before maximum growth rate is attained and this process occurred by plant roots. Phosphorus storage in plant depends on many factors such as plant type, litter decomposition rates, leaching of P from detrital tissue, and translocation of P from above to below ground biomass. However, phosphorus storage in aboveground biomass of emergent macrophytes is usually short-term, with a large amount of P being released during the decomposition of litter. Phosphorus is released back to the wetland after the plant decay. The aboveground portions of macrophyte returns P to the water, while below ground portions returns P to the soil (Reddy et al., 1999). From several researches, the results reported that the aboveground P standing stock values were in the range of 0.1-19 g P/m^2 and may amount up to 45 g P/m^2 for water hyacinth due to its high productivity.

2.5.2 Plant biomass and productivity

Primary productivity and biomass are the important parameters in wetland studies. In general, the productivity of emergent macrophytes is higher than that of terrestrial communities and agricultural crops because they do not suffer from shortage of water. Emergent macrophytes have high tolerance for the fluctuations in environment conditions and show high photosynthetic efficiencies. Wetlands with emergent macrophytes are often more productive than other wetland types and the primary productivity in wetland depends upon the type of wetland and the type of macrophyte found there as well as on hydrology, climate, and environmental variables such as soil type and nutrient availability.

2.5.3 Energy capture by plants

Wetland plant and animal communities exist in food chains where aquatic plants and algae are primary producers. They are basically capturing solar energy and converting it into energy-rich molecules, which finally form plant material. The actual yield of energy in plant depends on the product of solar input and efficiency with which the solar energy is transformed into the harvested product. An average solar radiation worldwide equal to 168 W/m^2 reported by (Masters, 1998) and because all of the light trapped in photosynthesis is ultimately released as heat, so that plant energy content is an important value using to estimate the energy capturing efficiency. The calorific values for many of the emergent species are in fact greater than those for the conventional fuel sources such as lignite coal and municipal waste shown in Table 2.3.

Long et al. (1992) reported that for most plant material, the calorific value of biomass will fall within the range 17-20 MJ/kg. Thailand is located in the tropical area with abundant sunshine, it is appropriate from the solar energy utilization to grow plants for use of both biomass production and waste recovery and recycling. However, only 1 to 5% of solar energy falling on a plant is converted to organic matter.

Table 2.3 Energy content of some emergent plants (Stephenson et al., 1980).

Species	Calorific value (KJ/g)
Cattails	15.4-19.6
Reeds and rushes	16.7-20.7
Sedges	15.4
Bulrush	17.7-18.4
Rice straw	18.9
Maize	19.5
Grasses	16.6-19.2
Lignite coal	15.9
Municipal waste	13.9

2.6 *Cyperus Papyrus* Linn.

In this study, Cyperus papyrus was used as the aquatic macrophyte in the CWs. Cyperus papyrus (*Cuperus papyrus* L.) is a tropical member of the sedge family (Cyperaceace family) which grows in water. Cyperus papyrus is a perennial, erect, emergent plant 2 to 4 m tall, with thick creeping rhizomes. The most important feature of the plants are the bright green, smooth, rounded stems. They grow in full sun, in wet swamps and on lake margins. It is native to central and northern Africa. The plant is used in paper-making in Ancient Egypt. To this day, expensive papers are made from papyrus using the original techniques. In southern Africa, the starchy rhizomes and culms are eaten raw or cooked by humans. The culms are also used for building materials. Young shoots are frequently grazed by livestock. In addition, papyrus is cultivated as a garden plant and is attractive when used for landscaping pools (Stephens and Dowling, 2002).

A research of a comparative of *Cyperus papyrus* and *Miscanthidium violaceum* based CWs for wastewater treatment in a tropical climate showed that papyrus could remove higher ammonium-nitrogen and total reactive phosphorus (TRP) (75.3% and 83.2%) than Miscanthidium (61.5% and 48.4%) and unplanted controls (27.9% ammonium-nitrogen). The suggestion is papyrus as having a greater potential to extract nutrients from wastewater due to the thin and loose root mat that allow water-plant interaction (Kyambadde, Kansiime, Gumaelius, and Dalhammar, 2004).

Okurut, Rijs, and Van Bruggen (1999) reported the design and performance of experimental constructed wetlands in Uganda, planted with *Cyperus papyrus* and *Phragmites mauritianus*. They suggested that the wetlands with Cyperus papyrus were effective in reducing BOD and COD to even lower levels than the Uganda standards. The removal rates for COD, NH_4^+ and o-PO_4^{3-} averaged to 3.75, 1.01 and 0.05 (g/m^2-d), respectively.

Chale (1985) indicated that papyrus swamps are efficient in nutrient removal for the purpose of domestic waste water renovation. This study was investigated in Kenya. It was conducted in a man-made impoundment transformed into swamp which received sewage effluents discharged into a stream. A comparison between the water quality characteristics of the influent and effluent from the swamp showed significant decreases in the mean temperature and conductivity by 20 and 23%, respectively. Dissolved oxygen was reduced by 85%, ammonium by 77% and orthophosphate by 80%.

Cyperus papyrus was utilized to plant into the plant bed filter systems for wastewater treatment. The purpose of this study more than treating the wastewater was related to resource recycling. Papyrus is one of the plants which are useful fiber materials and other products. This experiment was designed a wastewater treatment ditch in which terrestrial and perennial species can grow. The ditch contained baskets filled with bed filter material and were planted with higher plants. Cultivating of papyrus increased the N and P removal efficiency of the system (more than 50%).

This study was measured the standing biomass and the primary productivity of papyrus in Lake Naivasha swamp, Kenya. Papyrus aerial biomass and productivity in undisturbed swamp were estimated to be 3602 g/m^2 and 14.1 g/m^2-d, respectively. Then the peak in aerial biomass in the cut treatment was 2741 g/m^2. Papyrus aerial organs contribute approximately 75% of the total plant biomass and harvesting papyrus increased the culm-unit density to higher levels than the normal papyrus stands (Muthuri, Jones, and Imbamba, 1989).

2.7 Wetland Soil

Soil structure is an important component of wetland systems, especially for FWS system, because of its affect to hydraulic conductivity of the soil bed. The hydraulic conductivity should be about 10^{-3}-10^{-5} $m.s^{-1}$. Soil with some clay content can be very effective for phosphorus removal. Phosphorus removal in soil matrix can be a major pathway for almost complete phosphorus removal for many decades. In FWS wetlands, the only contact opportunities are at the soil surface, and the most active microbial activity occurs on the surfaces of the detritus layer and the submerged plant parts (Reed et al., 1995).

2.8 Domestic wastewater

Domestic wastewater means the water that has been used by community. It is derived principally from personal washing, laundry, food preparation, etc. and the like; sanitary wastewater; sewage. Where wastewater from sources other than typical domestic sources (e.g., industrial sources) is combined and treated with wastes from domestic sources, the determination of whether or not the wastewater treatment plant is designated as "domestic" shall be made by the Department considering any or all of the following: wastewater residuals classification; whether wastewaters have been pretreated or contain constituents within 50-150%, by concentration, of typical domestic wastewater; and whether the permittee, when not required to provide more stringent or otherwise specific levels of treatment, can provide assurance of facility compliance with domestic wastewater treatment standards (Department of Environmental Protection, Florida, www, 2003; Duncan, 2003).

The typical characteristic of untreated domestic wastewater is defined in Table 2.4. And the amount of discharged wastewater from the household, building is about 80% of total wastewater or can be seen in Table 2.5.

A research by Sasidhorn Buddhawong, Thares Srisatit, and Atchara Wongsaengchan (1995) was carried out to study the efficiency of two emergent plants, Cyperus corymbosus (chufa) and Elcocharis dulcis (spikerush), in CW with FWS wetlands for municipal wastewater treatment. Chufa and spikerush had the good performance to remove the nutrients over difference depth of water. Therefore, Vanier and Dahab (2001) suggested that CWs have been shown to provide sufficient domestic wastewater treatment in temperature climates.

Table 2.4 Typical composition of untreated domestic wastewater (Kriangsak Udomsinroj, 1993).

Composition	mg/L	g/cap/d
BOD_5	110-400	80-120
COD	1.75 × BOD_5	1.75 × BOD_5
TOC	0.8 × BOD_5	0.8 × BOD_5
Total Solids (TS)	350-1200	170-220
Total Suspended Solids (TSS)	100-350	70-145
Settleable Solids, ml/L	5-20	-
Grit	-	5-15
Grease	50-150	10-30
Total Nitrogen, as N	20-85	6-12
Organic nitrogen	0.4 × Total-N	0.4 × Total-N
Ammonia nitrogen	0.6 × Total-N	0.6 × Total-N
Nitrate nitrogen	(0.0-0.05) × Total-N	(0.0 – 0.05) × Total-N
Total phosphorus, as P	4-15	0.6-4.5
Organic phosphorus	0.3 × Total-P	0.3 × Total-P
Inorganic phosphorus	0.7 × Total-P	0.7 × Total-P
(ORTHO-P and POLY-P)		
Total alkalinity as $CaCO_3$	50-200	20-30
Chlorides as Cl	20-50	4-8
Sulfates as SO_4	15-30	-
Nitrate as NO_3	20-40	-
Phosphates as PO_4	20-40	-
Sodium as Na	40-70	-
Potassium as K	7-15	-
Calcium as $CaCO_3$	15-40	-
Magnesium as $CaCO_3$	15-40	-
Boron as B	0.1-0.4	-
Total Dissolved Solids	100-300	-

Table 2.5 Amount of untreated domestic wastewater per capita per day in Thailand.

Region	Wastewater rate (L/cap/d)					
	2536	2540	2545	2550	2555	2560
Central	160-214	165-242	170-288	176-342	183-406	189-482
North	183	200	225	252	282	316
Northeast	200-253	216-263	239-277	264-291	291-306	318-322
South	171	195	204	226	249	275

Source: Pollution Control Department, www, 1995.

Seni Karnchanawong and Jaras Sanjitt (1995) conducted a study to compare the efficiencies between facultative pond (FP) and water spinach pond to treat domestic wastewater. The results showed that the BOD, COD and SS mass removal rates increased as the mass loading rates increased and the water spinach pond was significantly more effective in reducing the organic content that the FP because of the aquatic plant.

2.9 Simulation model

Models have been widely used in environmental engineering since the late sixties when the discussion of pollution becomes worldwide. Then simulation model is a mathematical model that calculates the impact of uncertain inputs and decisions we make on outcomes that we care about and it can be considered as the synthesis of elements of knowledge about a system. Much of research was conducted to develop dynamic mathematical models to predict such as water quality, algae mass, bacteria mass of waste stabilization ponds and wetlands. On the other hand, the thermodynamic point of view becomes popular for simulating the model in ecology and industry because of its useful and sustainable concepts. The thermodynamic studies usually are based on the first law and second law of thermodynamics which related to energy, entropy, exergy and emergy. These earlier studies involved with dynamic mass and thermodynamic models are mentioned below in this section.

2.9.1 Parameters in the system

2.9.1.1 Primary productivity

Aquatic primary productivity in wetland consists of both phytoplankton and macrophyte: the basis for most aquatic ecosystems. This is of particular concern in water quality management because uncontrolled growth can cause taste and odor problems, unsightly algal scums, oxygen depletion in deeper waters, aquatic weeds etc. The measurement of primary productivity involves direct or indirect photosynthesis or the resulting biomass. In general, the growth of both plants and animals require energy. Plants get their energy from the sun through photosynthesis. Photosynthesis is the fixation of organic material by plants and *cyanobacteria* (blue-green algae). Moreover, photosynthesis is the process where the green pigment in the plant's leaf (chlorophyll) absorbs energy from sunlight and, using this energy, water, and carbon dioxide, produces oxygen and simple sugars; it is usually represented by the equation

$$6CO_2 + 6H_2O \xrightarrow{light} C_6H_{12}O_6 + 6O_2 \qquad (2.3)$$

The biosynthetic consequence is the light-mediated conversion of CO_2 to organic cell material. In an aquatic system, water can be considered as an unlimited resource and the carbon source is usually available as carbon dioxide or bicarbonate. So that solar energy is the important factor in the above reaction. However, how the plant uses its energy depends on the developmental stage of the plant and on environmental conditions. Within the life cycle of an organ, a plant, the total growth duration can be divided into three parts: slow growth early in season (exponential), rapid growth during midseason (linear phase) and a saturation phase for ripening. Therefore, the growth pattern typically follows a sigmoid curve or S-shaped (Goudriaan and van Laar, 1994; Sullivan, Hart, and Christensen 1999). Figure 2.7 shows the cumulative biomass accumulation by plant during the growing season. This pattern also occurs in the animal growth as the normal population growth rate.

2.9.1.2 Fish growth

Growth has many aspects. Growth in relation to e.g. age, temperature, ration, and body size can be described by entirely empirical mathematical equations and their importance as analytical models of growth are determined by the information contained in the parameters. The growth of a fish is considered as an interaction between the sample and the environment. The body size is a major factor to consider in the model because no realistic growth model of any application can ignore the influence of body size upon the growth processes.

2.9.1.3 Organic matter and nutrients

Organic matter (OM) and nutrients are important for living organisms in CW as substrate for macrophyte and fish in the systems. This is the advantages to remove OM and nutrients in CW. The way to reduce nutrients (nitrogen and phosphorus) in FWS wetland, is uptook by macrophyte (Chongrak Polprasert and Wong, 2004). In addition, OM which included OM from wastewater and plant, are consumed by fish in the system

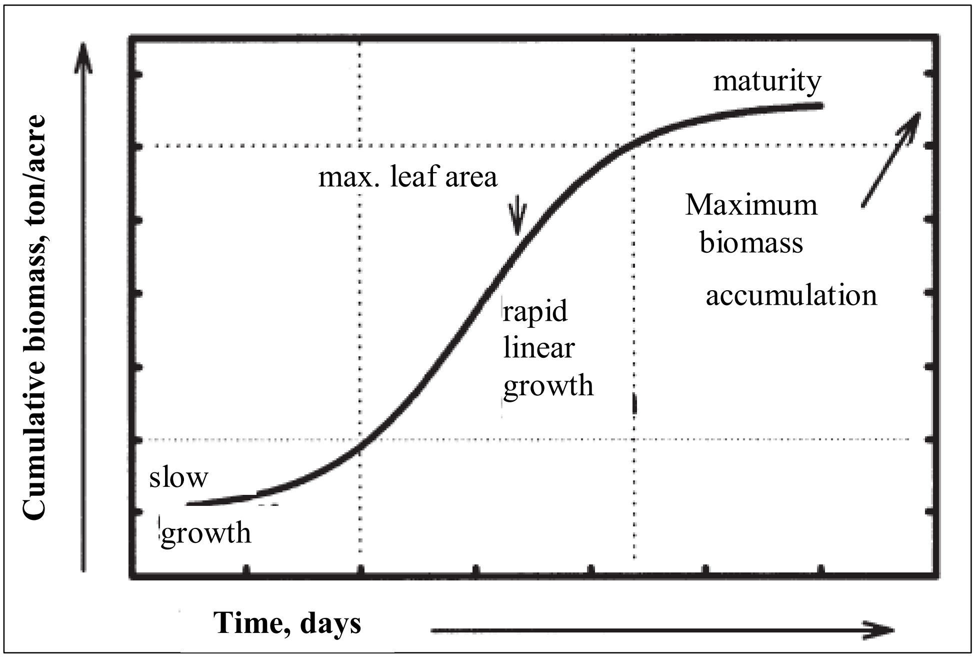


Figure 2.7 The sigmoid curve pattern of plant growth.

Cumulative N uptake also follows a sigmoid curve over the period of plant growing season. This cumulative graph is divided into three phases: slow N uptake corresponding to slow early phase of plant growth, rapid N uptake as the plant grows rapidly, and slow or no plant uptake (Sullivan et al., 1999). Figure 2.8 depicts the cumulative above-ground N uptake by the plant during the growing season.

2.9.2 Energy-model concept

Energy-model concept has been widely used to analyze ecosystem. It provides a useful method for evaluating the sustainability of a system. The first step of simulated model starts with the energy-flow diagram to help understand systems. So that the energy system language is helpful for converting verbal models into system network diagrams that show components and relationships. This language

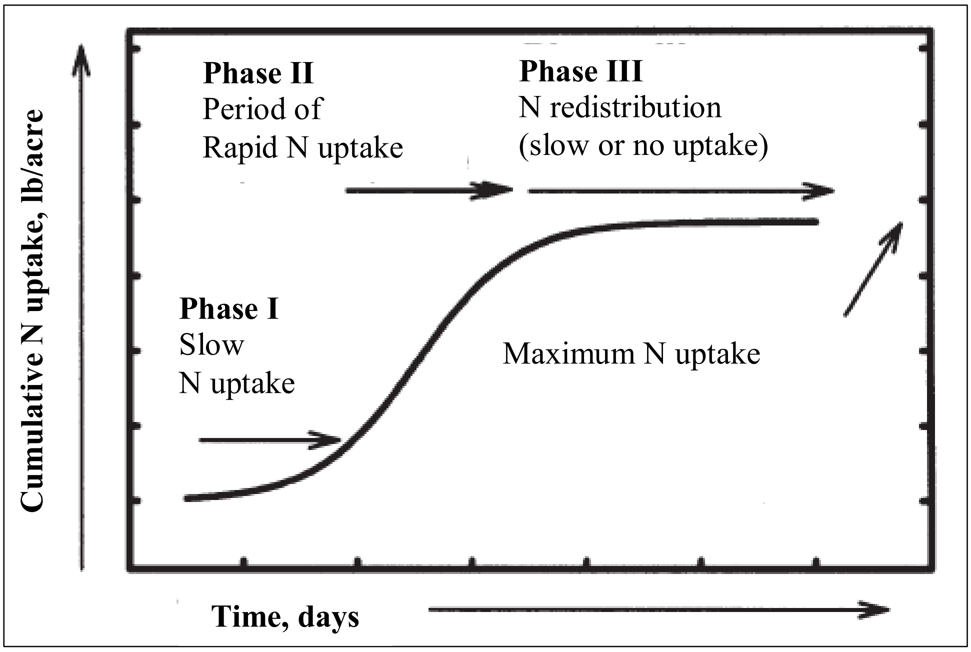


Figure 2.8 The sigmoid curve pattern of N uptake by plant.

demonstrates in the book "Systems Ecology" (Odum, 1983) and some useful of energy systems symbols from the book. Then the system diagrams become quantitative and can simulate by adding the calculated values for flows and storages.

There are many methods to analyze the energy flow models such as entropy, energy, exergy and emergy. However, emergy is an interesting method to quantify the energy because emergy is defined as the available energy of one kind required directly and indirectly to make a product or service. This method used the concept of an energy hierarchy to describe the work of nature that results in energy transformations. And the system of nature is interconnected in webs of energy flow. Thus, the appropriate energy type is sunlight which involved in almost every process in ecosystem. Sunlight is successively transformed from light to plant organic matter to herbivore, to carnivores, and so on. The energy is transferred from a lower energy quality to a higher quality. Thus, it is incorrect to use energy as s measure of work where more than one type of energy is concerned that why emergy is an interesting method to express all energy transfer (Brown and Ulgiati, 2004; Odum, 1988). The proportion of a product's emergy and its energy is defined as its transformity. Thus, solar transformity is the solar emergy required to make on joule of a service or product and its unit is solar emjoule per joule or sej/J (Odum and Peterson, 1996).

2.9.3 Previous modelling researches

Chongrak Polprasert and Nawaraj Khatiwada (1998) studied a model for organic matter removal in free water surface constructed wetlands. The conceptual model in this study related to both biofilm and suspended bacteria that normally contain in constructed wetlands, dispersion number and hydraulic retention time. The results demonstrated the significance of the biofilm bacteria present in the FWS constructed wetland in biodegrading organic matter opposite of suspended bacteria.

Moreno-Grau, García-Sánchez, Moreno-Clavel, Serrano-Aniorte, and Moreno-Grau (1996) conducted the experimental facility that was designed to compare the wastewater treatment efficiencies achieved in ponds using microphytes versus those using macrophytes and the aquatic macrophyte used in the study is *Phragmites communis* Tin. The model method is based on thermal sub-model and biochemical sub-model. Then it simulates temperature, suspended and attached bacterial mass, phytoplankton, zooplankton, dissolved oxygen, COD and nutrients. The result showed that the main difference encountered in the performance of ponds using microphytes or macrophytes is the higher dependency of the microphyte ponds on temperature. Moreover, the model in this study can be used to represent the behaviour of systems whose hydraulic regimes approach plug-flow conditions, including wastewater treatment ponds, river, or channels where rooted vegetation is present.

The several models which describe the fish population growth and mortality. Some of the growth parameters can be found in a book called "Handbook of Ecological Parameters and Ecotoxicology". There are eight methods to simulate the models which consist of: Exponential growth, Restricted growth, Logistic growth, Parabolic growth, Von Bertalanffy equation, Gompertz equation, Mortality, and Environmental factors. The growth curves as well as the total amount of energy or matter consumed over time may vary considerably during the growth period. It is suggested that the Gompertz or the parabolic growth models seem to be more suitable for the description of young fish growth (Gamito, 1998).

The useful of exergy and specific exergy indices as ecological indicators of the trophic state of lake ecosystems. Its reviews showed that the exergy has a good theoretical basis in thermodynamics and good to explain about the relation between exergy and eutrophication. In this study, biological and physic-chemical data were collected and biomass concentration of phytoplankton and zooplankton was determined from numerical density and individual body size. Moreover, organic matter content and the standing crop of submerged aquatic plants were estimated during the studying period. Finally, the sediment cores were collected by using Jenkins sampler (Ludovisi and Poletti, 2003).

Jorgensen explained that the thermodynamic concept exergy is defined as the better measure of the ecosystem because it has a few but advantages compared with the thermodynamic information (Jorgensen, Patten and Straskraba, 2000). Although, exergy is a more useful concept than energy, it only provides the information about the current state of the system and the ability to do work. It does not explain about which kind of energy is available for the system and it cannot distinguish among the different kinds of energy to do in the same work. Moreover, exergy concept does not provide the information about energy history of the product or service in terms of ecological inputs. These shortcomings are overcome by the concept of emergy (Bakshi, 2002).

The energy systems language is a methodology for converting verbal models in to system network diagrams showing mathematic, energetic, etc. for many purposes such as the facility of computer simulation program and evaluation of emergy. This study was developed blocks program to simulate model which called "EXTEND" program that is an easier way to generate model (Odum and Peterson, 1996).

Emergy was used to investigate the alternative way in ecological-economic method for wetland management. The wetland in Jackson Country, FL, USA was selected in this study because it has a heavily impact of Pb in the wetland environment. Three wetland management alternatives included land control, sediment excavation, and wetland restoration by replanting, were proposed. The emergy evaluation table with the important items from natural resources, imported resources, exports, and storage, were prepared to characterize emergy values for the environmental work. All energy sources that contribute to the economy were calculated in terms of solar emergy. The emergy-money ration is obtained by dividing the total solar emergy of the economy by the gross national product (GNP). Moreover, by dividing the solar emergy of any environmental inputs by the emergy-money ration, the amount of natural contributions, in terms of macroeconimic value, can be estimated. Decision on the use of resources in ecological management cannot be made correctly using money but an emergy comparison can be prepared for choosing among environmental alternatives. So that emergy was used to suggest the alternative management which is the restoration by replanting in this study (Ton, Odum and Delfino, 1998).

In the same way, method of emergy analysis was used to illustrate the economy of Thailand to provide fresh insight on proposals for constructing dams on the Mekong River. Emergy evaluation can make comparisons of alternative uses of resources to develop policies which maximize the total emergy flow in an economy. When two alternative systems were compared, the one which contributes the most emergy to the public economy and minimizes environmental losses is considered best (Brown and McClanahan, 1996).

Many earlier researchers have been used emergy to compare and evaluate the ecological sustainability of different system. A study was to analyze the use of resources in three different wastewater treatment systems consisted of conventional three-step treatment, conventional mechanical and chemical treatment complemented with a constructed wetland, and treatment in a natural wetland. And the other purpose was to illustrate the relationship between the demand for space, time and purchased input of these systems. The analysis of the treatment systems comprised the influent wastewater into the treatment units and return as a treated wastewater and likely residues (e.g. sludge) to the surrounding ecosystems. System boundaries were based on the treatment function of the three systems. The emergy analysis provided to convert resource use evaluated in the currency of emergy to an area demand. Moreover, empower density is the emergy inflow per unit time and area.

The comparison between the emergy density in a certain area relative to the surrounding ecosystems may indicate the level of human activity in that area (Geber and Björklund, 2001). Zuo, Wan, Qin, Du, and Wang (2004) also compared the ecological-economic benefits of different kinds of wetlands: the original wetlands and recently constructed wetlands in Yancheng Biosphere Reserve in China. Two new emergy indices, base emergy change (Bec) and net profit (Np), were calculated to choose the best system. The Bec index is a measure of the change of environmental quality and can also be used for evaluating the sustainability of an ecosystem. While considerable economic benefits can ensure adequate feedback to the system.

CHAPTER III

RESEARCH METHODOLOGY

Pilot-scale experiments were conducted at a site near the biological wastewater treatment plant of Suranaree University of Technology (SUT), to treat wastewater from the dormitories.

3.1 Experimental set-up

In this study, four different treatment systems used to carry out the experiments are as follows:

(a) Waste stabilization pond;

(b) Waste stabilization pond with fish;

(c) Constructed wetland with Cyperus papyrus and;

(d) Constructed wetland with Cyperus papyrus and fish.

The systems were made of concrete material, located near the biological wastewater treatment plant of SUT. The schematic layout of the unit system illustrates in Figure 3.1. The dimension of each system was 3.0 × 1.0 × 1.2 m (length × width × depth) planted with Cyperus papyrus on the gravel substratum of unique size (20 mm) at the bottom and the sandy loam at the top. Raw wastewater from dormitories of SUT was fed into each treatment unit, following the experimental schemes planned for observation of loading variations. The systems were operated, corresponding to waste

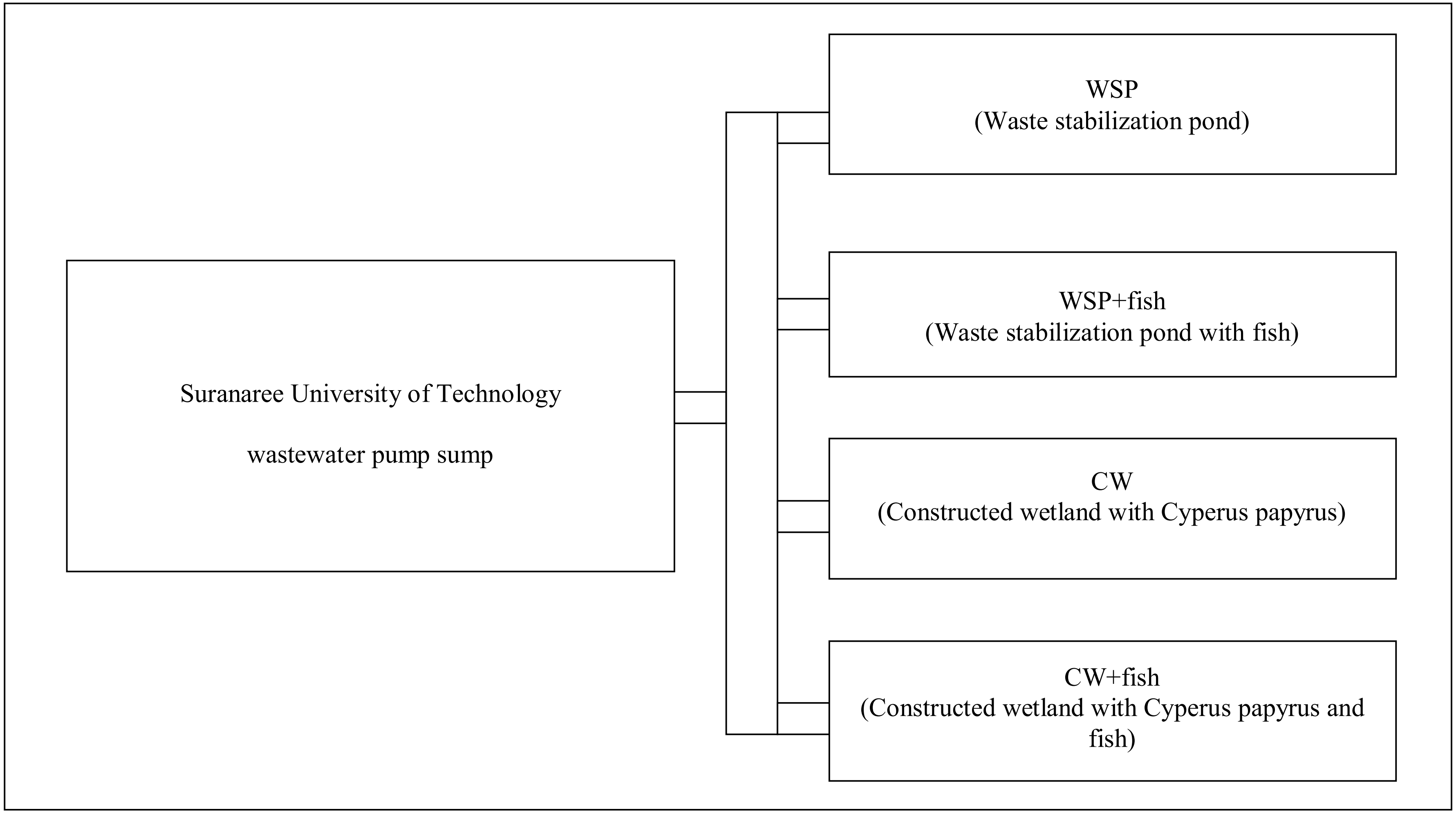


Figure 3.1 Schematic layout of waste stabilization pond and constructed wetland units.

depth reached to 0.35 m for free water surface wetlands and for waste stabilization ponds (WSP), the water level was adjusted at 0.9 m. In Figure 3.2 and 3.3 the side view of WSP and CW units are shown, respectively. Each system was operated with two units running in duplicate so as to ensure the accuracy of the data obtained. The CW and WSP units in the field site are shown in Figure 3.4 and 3.5.

3.2 Emergent plant and aquatic animal

3.2.1 Plant selection

Papyrus (*Cyperus papyrus* Linn.) which is in Family Cyperaceae was chosen in this study. The reason for this is that it is a useful plant. Papyrus is a perennial, erect, emergent plant 2 to 4 m tall, with thick creeping rhizomes. The most obvious features of the plant are bright green, smooth, rounded stems which are up to 40 mm thick at the base. Flowers are small and yellow-brown in color. They grow in narrow spikes 0.6 to 1.5 cm long which themselves are in cylindrical spikes 2 to 3 cm long (Muthuri, Jones, and Imbamba, 1989). This plant is easily cultivated and is suitable for medium to large water features, especially in warmer climates. So that it is an appropriate emergent plant for introducing in constructed wetland in Thailand.

3.2.2 Plant cultivation

These experiments are performed by selecting papyrus in the same age and size. Plants were grown for the first experimental run on October 15, 2004, in the CW beds at approximately 0.30 m intervals as shown in Figure 3.6. Then for the beginning of the experimental start up, all were cut down to 0.60 m height. In Figure 3.6, the plant were cut in the CW units, signaling the start of an experimental run. Afterward, water was fed into the systems with 0.35 m water depth for 2 weeks and

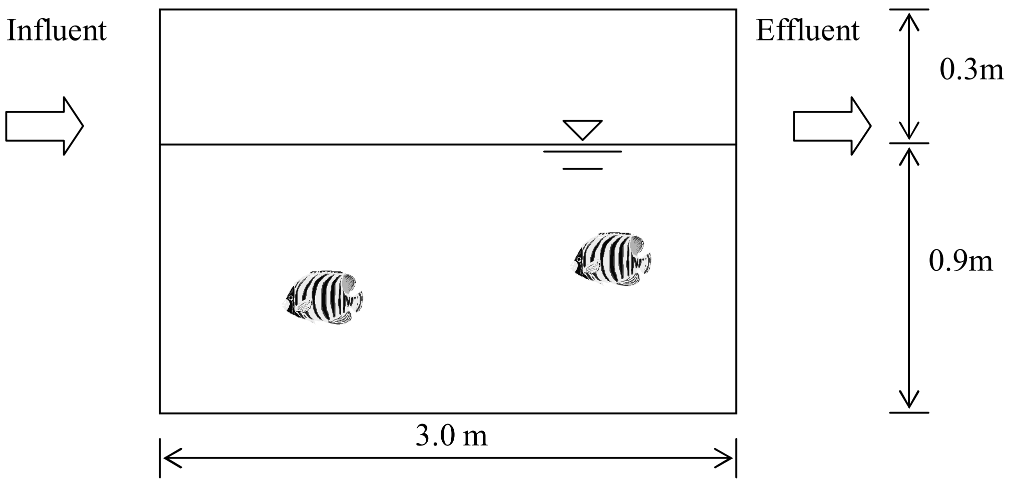


Figure 3.2 Side view of waste stabilization pond with Tilapia.

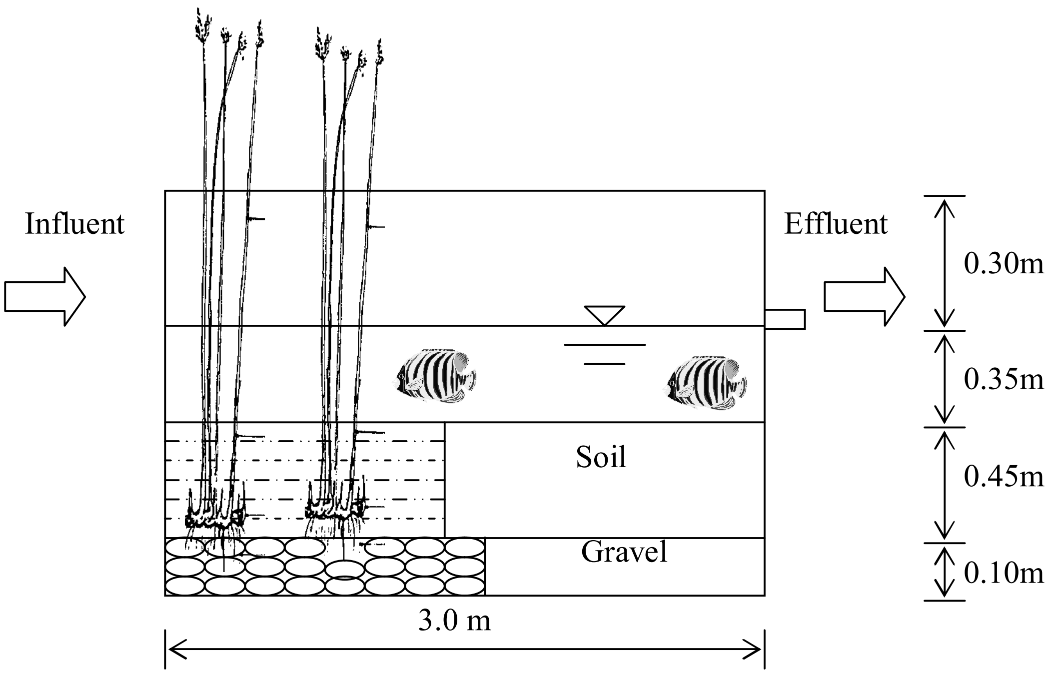


Figure 3.3 Side view of free water surface Constructed Wetland with Cyperus papyrus and Tilapia.

Figure 3.4 The reactors of constructed wetlands.

Figure 3.5 The reactors of waste stabilization ponds.

Figure 3.6 Cutting plant in constructed wetlands.

then domestic wastewater was fed continuously into the systems under the loading rate planned in the experimental runs.

3.2.3 Fish selection

Tilapia was the selected fish that is generally one of the most popular species cultured in Thailand. It is classified into omnivorous fish group which consumes both animals and plants (Chongrak Polprasert, 1996). All male fish were introduced into the treatment systems which their age and stock density were 3 months and 4 fish/m^2, respectively. In general, the average weight of 3-month fish is about 12 g and its length is 6 cm. After fish were reared into the units, tab water was fed into the nursery pond for 1 week and then domestic wastewater was discharged gradually into the systems. Consequently, fish were weighed and measured for the length on the first day of the experimental period. Then they were introduced into the treatment systems to begin the experiment.

3.3 Start-up of experiments

The experiment was begun by planting papyrus in the units. Then allowing the plants to grow for 3 months in wetlands and before the experiment began, the plants were allowed to acclimate with the feed for about a month. After that plants were cut down to 0.60 m in height above ground, signaling the first day of the experiment. Domestic wastewater was fed into all units at 0.35 m depth from the soil bed for the CW system (with and without fish) and the wastewater level in the WSP (with and without fish) was 0.9 m depth. Finally, tilapia fish were introduced into treatment systems responding with 4 capita per m^2. For the design criteria, the influent flow rates were designed by using equation (3.1) and (3.2) for WSP and wetland treatment systems.

$$Q = \frac{\forall}{t} \tag{3.1}$$

Where:

Q = flowrate, m^3/d

$\forall$ = volume of waste stabilization pond, m^3

t = hydraulic retention time, d

$$Q = \frac{LW(d_n n + d_w)}{t} \tag{3.2}$$

Where:

Q = flowrate, m^3/d

L = length of the wetland, m

W = width of the wetland, m

d_n = depth of the wetland soil, m

d_w = water depth, m

n = porosity, or the space available for water to flow through the wetland (0.4 for FWS system)

t = hydraulic retention time, d

In each system, four experimental runs were performed by varying the organic loading rate (OLR) for both WSP and CW. A batch flow feed format with variable volumetric loading to each sub units were used corresponding to the OLR of 10, 13, 31, and 63 kg BOD/ha-d, respectively. The sequence used of loading in all pond units were as follows: reading water level at the fixed point; draining off the wastewater about 30% of water volume to fixed drain level and finally loading wastewater up to the water level fixed for each pond. The details of each system are illustrated in Table 3.1 and 3.2, respectively.

3.4 Experimental Runs

This experiment was operated for 14 months. After starting the experiment, influent and effluent samples from WSP and CW were collected at every releasing days during the trial period 60 days in each experimental run to determine all parameters (BOD, COD, TSS, nitrogen and phosphorus). Afterwards, the experiments

Table 3.1 Details of the designed wetland in this study.

Run	Hydraulic retention time, d	Water depth, m	L:W ratio	Flowrate m^3/d	Hydraulic loading rate, mm/d	Organic loading rate, (kg BOD/ha-d)	Load Volume, m^3
1	18	0.35	3:1	0.10	35	10	0.312
2	12	0.35	3:1	0.16	52	16	0.312
3	6	0.35	3:1	0.31	104	31	0.313
4	3	0.35	3:1	0.63	208	63	0.315

Table 3.2 Details of the designed waste stabilization pond in this study.

Run	Hydraulic retention time, d	Water depth, m	L:W ratio	Flowrate m^3/d	Hydraulic loading rate, mm/d	Organic loading rate, (kg BOD/ha-d)	Load Volume, m^3
1	26	0.9	3:1	0.10	35	10	0.8
2	17	0.9	3:1	0.16	52	16	0.8
3	9	0.9	3:1	0.31	104	31	0.8
4	4	0.9	3:1	0.63	208	63	0.8

were set again by changing the corresponding OLR until completely operating in all runs. Furthermore, other parameters were analyzed for data collection. Physical features of wastewater such as temperature and pH were recorded on the days of water sampling.

3.5 Wastewater sample analysis

Collected samples were analyzed for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solid (TSS), ammonia nitrogen (NH_3-N), and orthophosphate phosphorus (o-PO_4^{3-}). These parameters were analyzed in the Environmental Engineering Laboratory at SUT according to the "Standard Methods" (APHA, 1998). Other physical parameters also were monitored, including pH, and temperature. The methods of analyses are given in Table 3.3 below. The characteristics of domestic wastewater from SUT are shown in Table 3.4.

3.6 Plant and fish harvesting

The plants were measured and determined for the biomass on the first day before the experimental began. Then, they were cut down about 0.6 m aboveground. After the reactors were carried out, plant height was measured at every 10 days, lasting two months long. Finally, their height were measured and cut for determining plant biomass and productivity at the end of the experiment and treated wastewater was drained out. The plant samples were analyzed for the biomass in the laboratory.

Table 3.3 Methods of parameters measured.

Parameters	Methods
BOD_5	Azide modification
COD	Close dichromate reflux
SS	Filtration/Evaporation
NH_3-N	Distillation
o-PO_4^{3-}	Vanadomolybdophosphoric acid Method
pH	pH meter
Temperature	Thermometer

Table 3.4 The characteristics of domestic wastewater from Suranaree University of Technology

Parameters	Range	Average
pH	6.15-8.31	7.23
Temp. (°C)	25.5-31	28.25
COD (mg/L)	32-184	108
BOD (mg/L)	7.80-34.80	21.30
TS (mg/L)	169.3-740	454.65
SS (mg/L)	2-44	23
NH_3-N (mg/L)	6.16-28	17.08
o-PO_4^{3-} (mg/L)	1.41-8.43	4.92

To determine the biomass, all materials were separately dried at 85°C to a constant weight. Hence the biomass in categories of culm and umbel (Mnaya, Asaeda, Kiwango, and Ayubu, 2007). Dry plant samples were pulverized with a hammer mill. Furthermore, some plant samples were ashed at 550°C for 8 hrs, and the ash was dissolved in 1 N HNO_3 for phosphorus analysis. Nitrogen concentrations in plant were determined by the macro-Kjeldahl technique. Moreover, the energy density of this plant was measured by using bomb calorimeter. For fish production determination, Tilapia fish were weighed and measured for the length on the first day before introducing into the treatment systems. Then fish were weighed every 15 days by using weighing scale to determine an average weight until the end of experiment.

3.7 Simulation model methods

A simulation model was developed to analyze energy and emergy values of a CW. The model simulates trends in CW, with particular emphasis on plant biomass and fish biomass. The simulation model methods are separated into several sections, beginning with a description of concerned parameters that were evaluated. Secondly, energy diagram and energy flow equations provide the overview picture of the component and interaction in the system boundary of constructed wetland in this experimental study and to calibrate the k-value for each flow in the system. Thirdly, emergy evaluation of constructed wetland with fish were investigated an energetic basis for quantification or valuation of energy used in the system boundary. The emergy analysis considers all systems to be networks of energy flow and determines the emergy value of the streams and systems involved.

3.7.1 A concerned finite element parameters in mass balance

3.7.1.1 Organic substrate and nutrients

Organic substrate support many of the living organisms in wetland and it is the main food for bacterial but also contain nutrients (N and P) enough to support the growth of wastewater microorganisms. Nitrogen and phosphorus in this study were mainly in the form of Ammonia and ortho-phosphate, respectively. Organic matter are in the soluble and solid forms. The important soluble organic substrate in wetland is in term of biochemical oxygen demand (BOD). Most soluble substrate is used by the suspended bacteria in the liquid flow and transport into the biofilm then consumed by attached growth bacteria. The organic solids applied to wetland, such as soil and litter, provide sites for material exchange and microbial attachment and is a source of carbon and energy that drive some of the important biological reactions in wetland. This part of organic matter was utilized by fish in the system. In this study, low-strength wastewater was fed to the systems. A substrate mass balance in this experimental wetland can be expressed by the input substrate, output substrate, substrate and substrate consumption by fish. However, we assumed that fish received energy from plant more than energy from wastewater because of low content of organic matter in the wastewater.

3.7.1.2 Fish

Tilapia was selected to introduce into the wetland in this study. It is classified into omnivorous fish which consumes both animals and aquatic plants. This fish is disease-resistant, reproduce easily, eat a wide variety of foods and tolerate poor water quality with low DO levels. In this model, it is presumed that fish consume organic solid in the influent and submerged plant parts in the pond, and algal cells produce from the photosynthetic reaction. However, the amount of algal cells in CW was smaller by comparing with the aquatic plant because it was shaded by above ground part. So that it was eliminated in this energy diagram. Moreover, fish lived in the aerobic zone where oxygen and food are present and consume O_2 produced from translocation of plant root, algal photosynthesis and natural surface reaeration for their growth. Another significant factor is the survival rate pertaining to the presence and/or absence of plant grown in the CW serving as shelter and food source for their living. The increase of fish productions depend on only the growth rates of fish and the fish reproduction is negligible because only male fish were reared in the wastewater treatment.

3.7.1.3 Plant

Plant grown in the CW is papyrus. It is an emergent plant belonging to the sedge family. The plants are easily cultivated and suitable for medium to large water features, especially in warmer climates. The most dominant feature of the plants are the bright green, smooth, rounded culms (flowering stems) which are up to 40 mm thick at the base and may be up to 5 m tall in ideal conditions. The topped part of this plant is called umbel. It consists of a dense cluster of thin, bright green that is the principal photosynthetic organ of the plant. Papyrus can growth well in the full sun but shelting from the wind.

Papyrus is the photosynthetic autotroph using inorganic carbon from the atmosphere above as a carbon source and sun radiation as the energy source. Inorganic carbon in the atmosphere is an enormous amount compared with that the wastewater. So that it is assumed constant in this simulation model. The major benefit of plant is the transferring of oxygen to the root zone. It is an important part for improving water quality because it can be increased the surface areas for attached growth bacteria that use oxygen for many processes such as nitrification, bacterial respiration, etc. and plant root systems may provide a high-surface-area fixed biofilm substrate. Moreover, the submerged portions of plant in wetland were served as the substrate for fish and plant can be used as the shelter for fish rearing.

In this study, papyrus in the simulation model varies with the plant growth rate and death rate. Plant growth rate is related to the plant productivity. It is the fixation of solar energy by plant in the form of organic chemical bounds. This energy capturing provides an energy source for metabolism and growth of the plant and subsequently provides an energy source for heterotrophs which consume this plant tissues. Photosynthesis requires solar energy, CO_2, and H_2O. It also requires other parameters such as nutrients, enzymes, and plant structures but the main factor for plant growth is the input of energy from sun radiation at the global averaging rate of 168 W/m^2 (approximately 12 h/d). Papyrus is a perennial plant and can re-grow rapidly after it has been harvested and can probably regain its original biomass within nine months to a year. However, in this study, papyrus was planted for only 2 months in each experimental run so that the death rate will be eliminated because of the short time compared to the plant's life cycle.

3.7.2 Energy model

The emergy accounting based on embodied solar energy for assessing the energy transfer and relationship among each compartment in CW treating low-strength wastewater. This study evaluated emergy of CW which involved plant and fish growth as the food chain and treatment performance in the system. The trophic dynamic defined as the aspect of ecology that was initiated a qualitative and quantitative approach to ecosystems by focusing on the energy transfer efficiency and utilization (Higashi et al., 1993). Consequently, step-by-step procedure is given next:

Step 1: Energy system diagram

A system diagram in overview was drawn first to scope the system boundary, put the important parameter in perspective, and to organize data gathering efforts. In this study, the energy language symbols were used to depict the system diagram as shown in Figure 3.7. After a boundary of the system is indicated with a rectangular frame, outside influences are shown with source symbols (circles) arranged from left to right in order of increasing transformity. Within the frame, main components such as producers, consumers, storages and interactions are shown by arranging symbols form left to right according to energy intensity. The flows or pathways are connected between each component and describe by using an equation or mathematical relationships such as adding, multiplying, integrating, etc. Afterward a complex diagram was drawn, further it was simplified by aggregation and indicated inputs, flows and storages with the variables as depicted in Figure 3.8. Consequently, the diagram of the system is used to set the energy equations and it is used to construct a table of data requirements for the emergy analysis.

Step 2: Simulating energy equation

Energy analysis was used to make an overview of CW which fish were introduced into the system. The energy diagram is shown in Figure 3.9 was labeled as the pathways with algebraic expressions and the difference equations as mentioned in the abbreviation before.

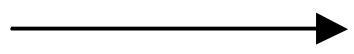
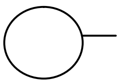
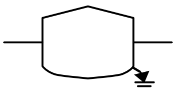
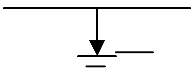
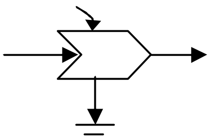
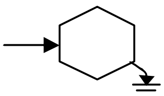
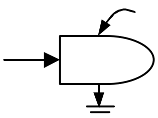
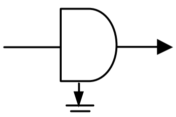
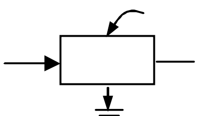
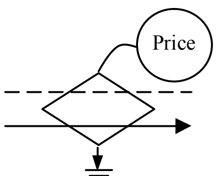
	Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.
	Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.
	Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.
	Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.
	Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.
	Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.
	Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.
	Self-limiting energy receiver. A unit that has a self-limiting output when input driven are high because there is a limiting constant quality of material reacting on a circular pathway within.
	Box. Miscellaneous symbol used for whatever unit or function is labeled.
	Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 3.7 Explanation of symbols of the energy systems language (Odum, 1983).

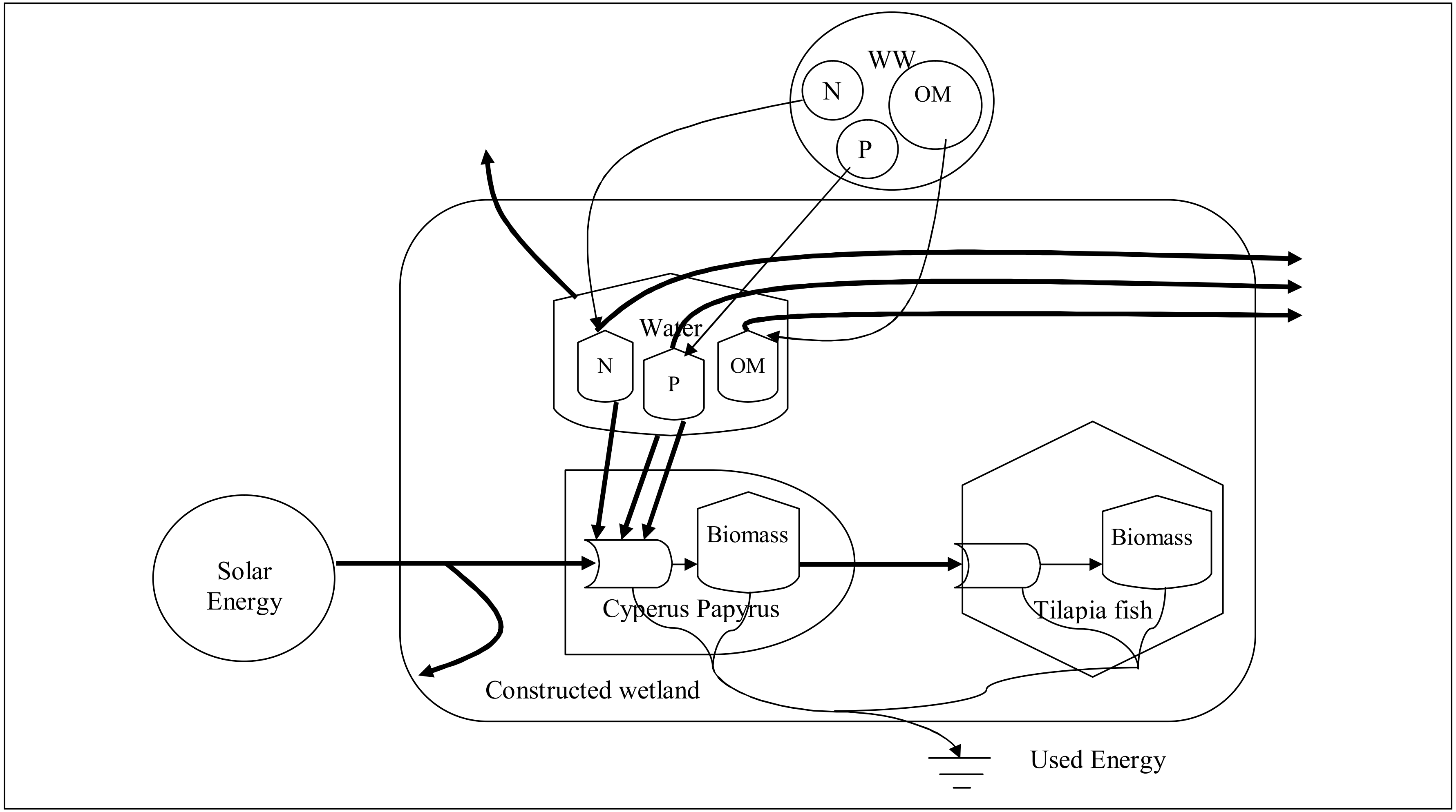


Figure 3.8 Energy diagram of the constructed wetland system.

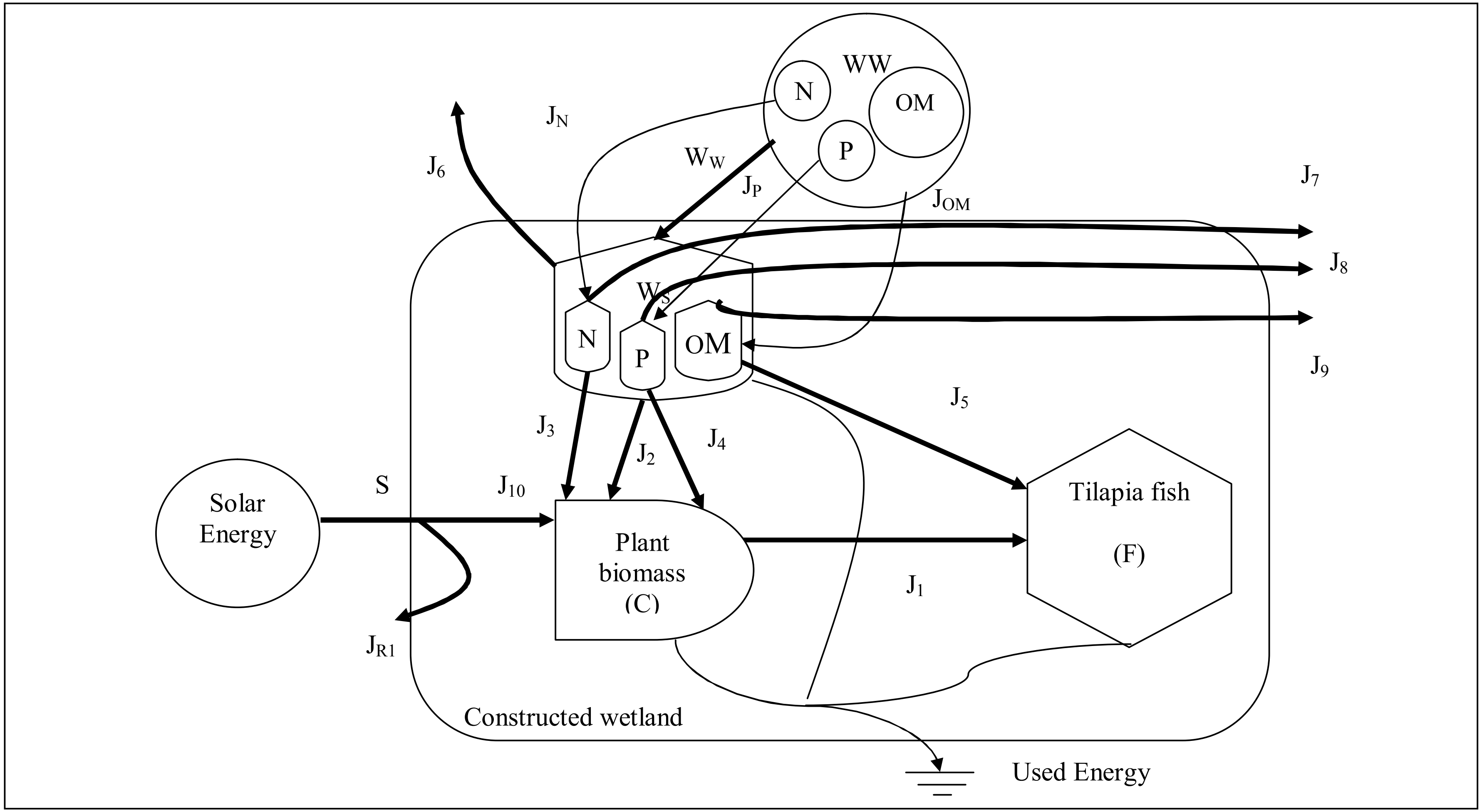


Figure 3.9 Aggregated energy diagram of the constructed wetland system.

Mathematical relationships are already assumed from the aggregated energy diagram since each pathway has a characteristics term that goes with each kind of symbol-pathway pattern. Thus a set of equations have been written by inspection, one equation for each unit in the diagram that has storage properties. Then the flow equations related to important storages, were combined together which depended on the inflow and outflow directions. There are six basis equations that they are composed of water storage (W_S), plant production (C), fish production (F), nitrogen storage (N), phosphorus storage (P) and organic matter storage (OM) as expressed below:

$$dW_S/dt = W_w - (k_2*W_S) - (k_6*W_S) \tag{3.3}$$

$$dC/dt = (k_{10}\times W_S\times N\times P) - (k_1*F*C) \tag{3.4}$$

$$dF/dt = (k_1*F*C) + (k_5*OM*F) \tag{3.5}$$

$$dN/dt = J_N - (k_3*N) - (k_7\times N) \tag{3.6}$$

$$dP/dt = J_P - (k_4*P) - (k_8*P) \tag{3.7}$$

$$dOM/dt = J_{OM} - (k_5*OM*F) - (k_9*OM) \tag{3.8}$$

Where the abbreviation of input, flows and storages are defined as:

S = Sun over specific area

J_{R1} = Remainder sun available

C = Plant biomass

F = Fish biomass

J_1 = Plant consumed by fish = $k_1 \times F \times C$

J_2 = Water used by plant = $k_2 \times W$

J_3 = Nitrogen uptake by plant = $k_3 \times N$

J_4 = Phosphorus uptake by plant = $k_4 \times P$

J_5 = Organic matter consumed by fish = $k_5 \times OM \times F$

J_6 = Treated wastewater = $k_6 \times W$

J_7 = Nitrogen outflow = $k_7 \times N$

J_8 = Phosphorus outflow = $k_8 \times P$

J_9 = Organic matter outflow = $k_9 \times OM$

J_{10} = Sunlight received by plant = $k_{10} \times W \times N \times P$

J_N = Nitrogen inflow

J_P = Phosphorus inflow

J_{OM} = Organic matter inflow

W_W = Wastewater inflow

WW =Wastewater

W_S = Water storage

N = Nitrogen storage

P = Phosphorus storage

OM = Organic matter storage

k_1 = the energy transfer coefficient between plant and fish

k_2 = the energy transfer coefficient between water storage and plant

k_3 = the energy transfer coefficient between nitrogen storage and plant

k_4 = the energy transfer coefficient between phosphorus storage and plant

k_5 = the energy transfer coefficient between organic matter storage and plant

k_6 = the energy transfer coefficient of treated wastewater outflow

k_7 = the energy transfer coefficient of nitrogen outflow

k_8 = the energy transfer coefficient of phosphorus outflow

k_9 = the energy transfer coefficient of organic matter outflow

k_{10} = the energy transfer coefficient between sunlight and plant

Plant production flow (J_{10}) was a function of sunlight, nutrients from wastewater including nitrogen and phosphorus, and water for photosynthesis process. Energy flow from plant production (J_1) was captured by fish and stored as fish production. Also, fish consumed organic matter from wastewater (J_5) but it is eliminated since it was assumed that it had less amount than the submerged part plant. The change of wastewater or water storage depend on the energy flow of wastewater input (W_W), water used by plant (J_2), nutrients uptake by plant (nitrogen uptake flow (J_3) and phosphorus uptake flow (J_4)), organic matter consumed by fish (J_5), treated wastewater outflow (J_6), nitrogen outflow (J_7), phosphorus outflow (J_8) and organic matter outflow (J_9). This energy model was helpful for further simulating emergy and transformity values of plant biomass, fish biomass and water storage.

Next, the emergy indices of constructed wetland are evaluated by using emergy analysis table. Furthermore, the emergy in each important item was evaluated for many purposes such as to determine waste removal efficiency.

Step 3: Emergy analysis table

After the energy diagram and energy equations were investigated to show the main inputs and flows. The solar emergy values were calculated for the main flows and storage of interest and expressed in an emergy analysis table. The important data provides in the tables, consisted of the interesting items, actual units of the flow, transformity of the item and solar emergy. In most cases, data obtained from the experiments of earlier studies but when no appropriate data were available, new values were calculated. The emergy of each item was calculated by this equation:

$$M = Tr \cdot E \tag{3.9}$$

Where :

M = emergy (sej/time)

Tr = transformity (sej/unit)

, E = the available energy or mass (mass/time or joules/time).

Emergy analysis table is divided into 4-column, the first column provides the detail of items and footnote number that contains sources and calculations for the items. Then the raw data values were added in the second column as the actual units of the flow, usually evaluated as flux per time. Most often the units are energy (joules/time), but sometimes are given in gram/time. The raw data are multiplied by the transformities in the third column to obtain the solar emergy in the fourth column. Transformity of the item, usually derived from previous studies. Finally, the format of calculations prepare for using as the raw data, demonstrates in the next table.

Step 4: Model Parameters and Calibration

Data from the experiment was used to calibrate the model. Coefficient values were calculated for the assumption as inflows to storage equal outflows from the storage. Then it was simulated with the computer program. In this study, we used a Microsoft Excel spreadsheet program as a tool to predict the energy storage in each parameter of CW. The first spreadsheet contains with the description, variable, equation, calibration value and k-value of each item. Then a simulation model spreadsheet was linked with the first one according to storage values and k-value. Model equations were established to describe flows in the CW system and also aggregated energy diagram was shown to overview the pathway in the CW model. Finally, emergy evaluation table of this experiment was also provided for the comparison it with other experimental runs by focusing on the waste removal efficiency, plant production efficiency and fish production efficiency.

CHAPTER IV

RESULTS AND DISCUSSION

The four different treatment systems were designed, following two categories: constructed wetlands (CW) and waste stabilization ponds (WSP), each with and without fish. The influent and effluent concentrations of wastewater in all units during these four experimental runs as well as the plant productivity and fish production were determined at frequent intervals. Additionally, the energy capturing efficiency of papyrus is one of interesting topics that helps us managing the harvesting period and manpower. Finally, the simulation model is helpful for predicting the relationship between water quality, plant and fish production in the other CW.

4.1 Water quality

4.1.1 pH

During the experimental period, the influent pH values in four experimental runs of CW and WSP were about 6-8. Similarly, the effluent pH of both CW with and without fish value was nearby in the range of 7-8 which was lower than that the effluent pH values of WSP with and without fish. They ranged from 7.5-10 for all WSP units which are rather to be alkalinity. Details of the experimental data are shown in Appendix A.

pH is an important parameter because it influences on other chemistry. Many treatment bacteria are influenced by the pH such as bacteria in the nitrification and denitrification processes. Aquatic plant, wildlife and wastewater chemistry and biology are also affected by pH. In this study, tilapia fish was introduced in the systems and it can resist pH very well in the range of 6.5-8.3. Moreover, papyrus which is the emergent plant in this experiment, can tolerate pH of 6.0-8.5 which is approximately the same as fish. According to the pH results, the pH condition of CW in this study is suitable for tilapia to survive and offer this plant to grow well. At the same time, an average effluent pH from WSP is higher because of algae in the system. Algae growth has the opposite effect on WSP pH. It used carbon dioxide and bicarbonate for growth to produce hydroxyl ions that cause pH rising to be alkalinity. Although, the steeper trend in the WSP pH caused by algae growth, caused photosynthetic activity and utilizes bicarbonate ions. Natural disinfection is effective at the higher pH. Phosphorus removal by natural chemical precipitation is greatly enhanced at pH values greater than pH equal to 8.5. In addition, an efficiency of ammonia stripping to the atmosphere is increased when pH rising.

4.1.2 Temperature

This experiment was constructed at Suranaree University of Technology. It is located in north-east of Thailand that is in tropical-climate area, high of both temperature and humidity. During the experimental period, mean influent and effluent wastewater temperatures of both CW and WSP were in the range of 25-31°C. Details of the experimental data are shown in Appendix A. Furthermore, CW had lower water temperature than WSP about 1-2 °C because papyrus in the wetland systems intercepted solar radiation before reaching the wastewater. In this experiment, wastewater temperature condition of CW is suitable for papyrus and tilapia growth because the optimum water temperature for papyrus is in the range of 20-30 °C and tilapia can tolerate the temperature up to 40°C.

4.1.3 Biochemical oxygen demand (BOD) and total suspended solid (TSS)

Biochemical oxygen demand (BOD) is a measure of the oxygen consumption of microorganisms in the oxidation of organic matter. Settleable organics are rapidly removed in wetland systems by quiescent conditions, deposition, and filtration. Attached and suspended microbial growth is responsible for removal of soluble BOD.

Appendix A. indicates the data of influent and effluent BOD variations during the experimental period profiles. The influent concentrations were ranged in 18.0-23.9 mg/L that are quite lower comparing to the domestic wastewater elsewhere in Thailand. The BOD effluent concentrations for CW with and without fish were 5.63 and 5.10 mg/L for Run 1, 6.16 and 5.55 mg/L for Run 2, 8.57 and 8.29 mg/L for Run 3, and 10.65 and 10.52 mg/L, respectively. For WSP with and without fish, the effluent contents varied 21.43 and 21.21 mg/L for Run 1, 18.04 and 17.74 mg/L for Run 2, 13.12 and 13.01 mg/L for Run 3, and 12.87 and 12.51 mg/L for Run 4, respectively. The discharged wastewater concentrations of almost all units achieved the standard which cannot exceed than 20 mg/L. However, the effluent of WSP in Run 1 was a bit higher (7%) than that the standard level. The average removal efficiencies for BOD were among 42-76% for wetland systems and as for WSP systems, the mean effluent removal efficiencies for all type units were low in the range of 3-30%.

In the same way, the average TSS influent concentrations of all units varied between 10.86-16.41 mg/L and the TSS effluent concentrations of CW with and without fish ranged from 3.50-9.93 and 4.29-9.50, respectively. The removal efficiencies of CW with and without fish were in the range of 27-74% and 23-79%, respectively. In contrast, TSS in overall WSP effluents were higher than that the influent. The average TSS concentrations were in the range of 14.38-16.31 mg/L, 15.85-20.65 mg/L and 16.68-19.93 mg/L for WSP influent, WSP with and without fish units, respectively. WSP systems discharged more turbid effluent than that the influent, the major source of that exceeded suspended solids, came from algae cells. The data of inflow and outflow concentrations used to determine the TSS removal efficiencies, are given in Appendix A.

The removal of suspended sediments is a major function performed in wetland ecosystems by the physical processes. The wastewater passes through the free water surface wetland with the low velocity including the depth of wetlands, gives an estimate of the time and distance that causes the TSS settle down via gravity in the initial length of the units. The dense papyrus in the wetland also helps to remove TSS remaining in the wastewater by filtration including sedimentation and biodegradation by bacteria attached to plants. In contrast, algae grew well in WSP units because they are not shielded by plant, while the algae growth in wetland is limited by emergent plant in the system. Accordingly, the shallower depth and the presence of the aquatic macrophyte are the major differences between wetland and waste stabilization pond.

The removal efficiencies between CW with and without fish were not significantly ($P>0.05$) different for all runs which is the same as WSP with and without fish. Moreover, The BOD removal efficiency values of both CW with and without fish were significantly higher than values for both WSP with and without fish ($P<0.05$). BOD removal efficiencies of wetlands decreased with the organic loading rate (OLR) but for WSP, the removal efficiencies increased with the OLR. The removal efficiencies resulting in different OLR are presented in Figure 4.1. From the results, the mean effluent BOD removal efficiencies of CW and CW with fish in each Run were significantly different ($P<0.05$) except the efficiencies between Run 1 and Run 2 including Run 3 and Run 4. Furthermore, the mean BOD removal efficiencies of WSP and WSP with fish in each Run were significantly different ($P<0.05$) except only between Run 2 and Run 4. Figure 4.1 also suggests the optimum OLR of about 30 kg BOD/ha-d which should be used to calculate the maximum size of maturation pond in the WSP system. At the OLR's below 30 kg BOD/ha-d, the algal growth predominates, resulting in the effluent BOD value higher than that of influent and consequently wasting the larger land area for constructing the pond. Meanwhile, at the OLR's higher than 30 kg BOD/ha-d, the hydraulic retention time is not enough for the bacteria to oxidize the organic BOD well below the standard level.

TSS removal efficiencies of wetlands decreased with the organic loading rate (OLR) but for WSP, the removal efficiencies increased with the OLR and almost constant between Run 3 and Run 4. The removal efficiencies resulting in different OLR are presented in Figure 4.2. The results showed that the removal efficiencies between CW with and without fish were not significantly different ($P<0.05$) in all Runs which also occurred in WSP with and without fish. Besides, the TSS removal efficiencies of both CW with and without fish were significantly ($P<0.05$) higher than values for both WSP with and without fish.

From the results, the phenomenon of BOD and TSS removal performed in the same trend. This finding demonstrates that the treatment performance of BOD was associated with TSS existing in the system units. The BOD effluent from WSP

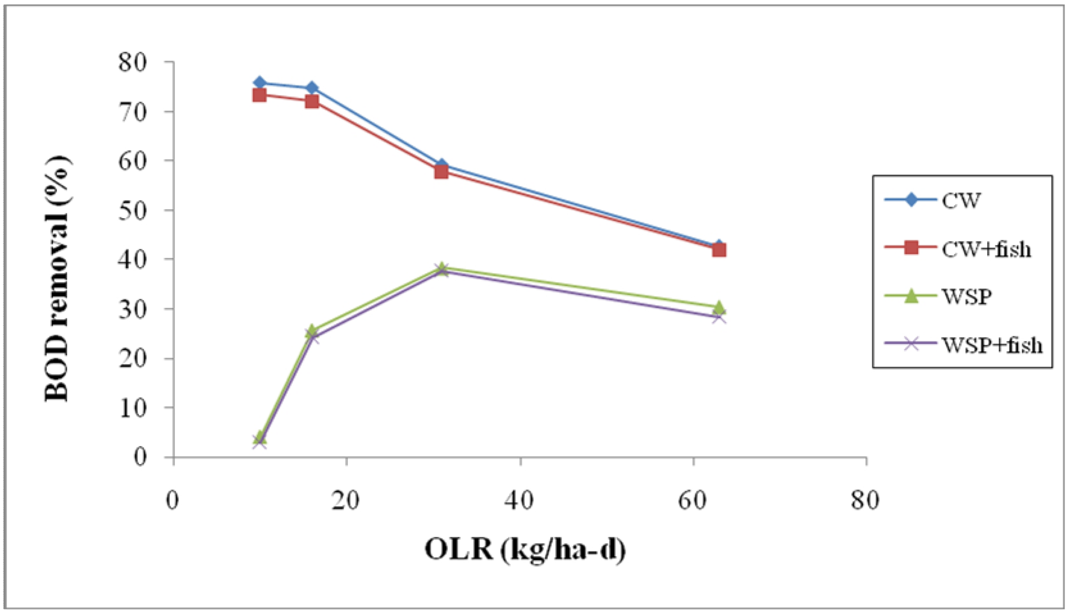


Figure 4.1 The BOD removal efficiencies versus OLR of CW, CW with fish, WSP, and WSP with fish.

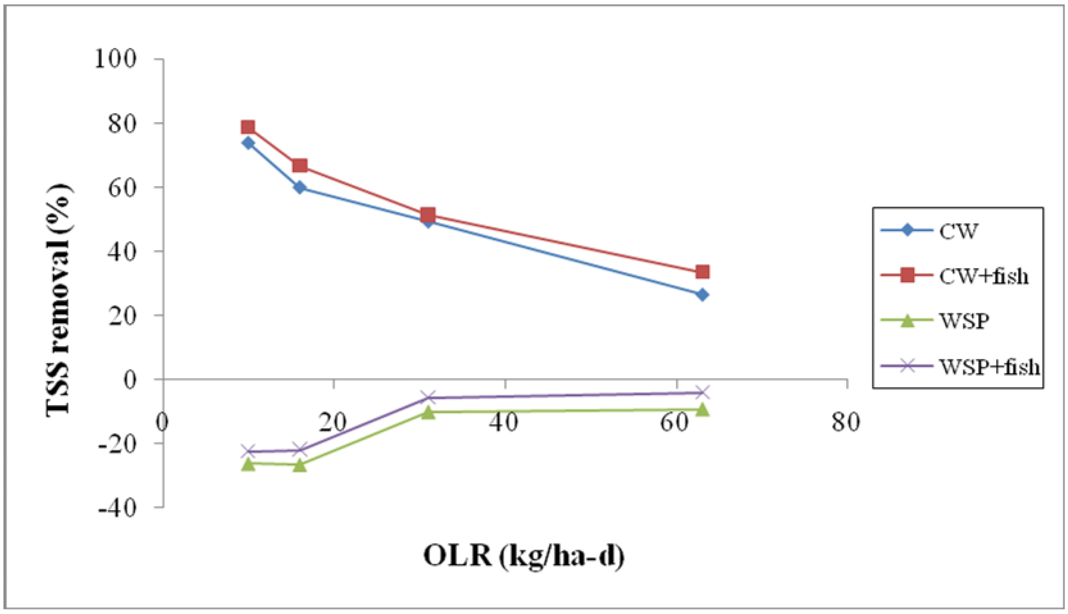


Figure 4.2 The TSS removal efficiencies versus OLR of CW, CW with fish, WSP, and WSP with fish.

systems were higher than wetland effluents maybe by the algal cells in the systems. In WSP systems, algae had grown cover the water surface, reaeration is prevented, depletion of oxygen may occur, and assimilation of BOD is reduced. On the other hand, wind-induced water mixing and algal production will be reduced by a densestand of emergent plants in the wetlands. Papyrus has the dense mat root that can translocate a lot of oxygen from the atmosphere through the plant to the root zone that can help to improve BOD in the below-ground wetlands. Furthermore, CW, the system with plant, can improve more removal efficiency than that of WSP because aquatic plant tends to absorb some organic substances for its growth and plant helps wastewater to circulate well in the system. The correlation in the graphs of Figure 4.1 and 4.2 indicates that the good performance occurred at the lower organic loading rate or higher HRT for CW. But for WSP, the highest removal efficiency was observed at Run no.3 which made the optimum organic loading rate for WSP to be at 30 kg BOD/ha-d. At the organic loading rate lower than that, CW should be applied to better improve the treatment performance than that of WSP, for example, replacing maturation pond. The reason is, at the lower organic loading rates which are long retention time, there were a lot of algal cells growing in the systems which produced more suspended solids in the effluent than that of the influent. And they happened to reduce the ability of BOD removal. On the other hand, plant in wetland helped to remove TSS in the unit both direct and indirect ways so that TSS removal efficiencies reached almost 80% in this study.

4.1.4 Chemical oxygen demand (COD)

The chemical oxygen demand (COD) is commonly used to indirectly measure the amount of organic compounds in wastewater. In wetlands, microbial plays the dominant role in the removal organic matter in the wastewater. Furthermore, removal of organic materials in the CW system mainly depends on the metabolism of heterotrophs. The COD of the waste is, in general, higher than the BOD because more compounds can be chemically oxidized than can be biologically oxidized.

The COD concentrations of wastewater in this study were quite low comparing with elsewhere domestic wastewater. The influent contents were fluctuated in the range of 65.43-92.39 mg/L and 68.35-96.70 mg/L for CW and WSP systems, respectively and the release wastewater during the four experimental period ranged in 31.76-54.27 mg/L, 29.22-56.73 mg/L, 55.29-66.16 mg/L, and 46.46-61.29 mg/L for CW with fish, CW without fish, WSP with fish and WSP without fish, respectively. Inflow and outflow rates of each experiment were used to obtain the COD removal efficiencies. The average removal efficiencies for CW with fish, CW without fish, WSP with fish and WSP without fish were in the range of 65.62-21.12%, 68.38-17.54%, 19.10-40.38%, and 20.14-43.58%, respectively. The experimental data are shown in Appendix A.

The removal efficiencies of all CW systems both with and without fish tend to be decreased with the OLR increasing or retention time decreasing and for WSP systems both with and without fish, the removal efficiencies was highest at Run 2, corresponding to 16 kg BOD/ha-d of OLR and tended to decrease with higher OLR. If we consider the COD removed solely by heterotrophs, longer HRT should have higher removal efficiency. The removal efficiencies between CW with and without fish were not significant ($P>0.05$) different for all Run which is the same as WSP with and without fish. Moreover, The COD removal efficiencies were not significant ($P<0.05$) different in all units for Run 3 and Run 4. The reason would be due to very low values of the influent COD contents in the systems. In addition, the removal rates were slightly reduced ($P<0.05$) between Run 1 and Run 2 of both wetland systems as shown in Figure 4.3.

4.1.5 Ammonia nitrogen (NH_3-N)

Ammonia nitrogen is important in wetland and other surface water because it is the preferred nutrient form of nitrogen for most wetland plant species and for autotrophic bacteria species. Removal mechanisms of ammonia nitrogen in the CW are volatilization of ammonia, nitrification/denitrification, and plant uptake (Polprasert, 2004; IWA, 2000).

The influent ammonia nitrogen concentrations in this study were in the range of 10.66-23.86 mg/L and the effluent concentrations varied between 1.96-8.71 mg/L and 4.56-9.14 mg/L for CW and WSP systems, respectively. Inflow and outflow data were measured to determine the removal efficiencies as presented in Appendix A.

CW with and without fish had NH_3-N removal averaging 20-86% and 18-89%, respectively, while the ponds achieved 14.5-76% for units with fish and 20-68% for units without fish in the case of removal of NH_3-N. The NH_3-N treatment performances in the CW were generally better than those for the WSP. Specific mass removal rates of CW and WSP systems were in the range of 18-37 g/d and 9-31 g/d, respectively. The high ammonia nitrogen removal of CW systems may be explained by the ability of many emergent aquatic macrophytes to transport oxygen down to the roots, thereby establishing an oxidized rhizosphere (Armstrong, 1964). The oxidized layer and the submerged portions of plants are important sites for nitrification in

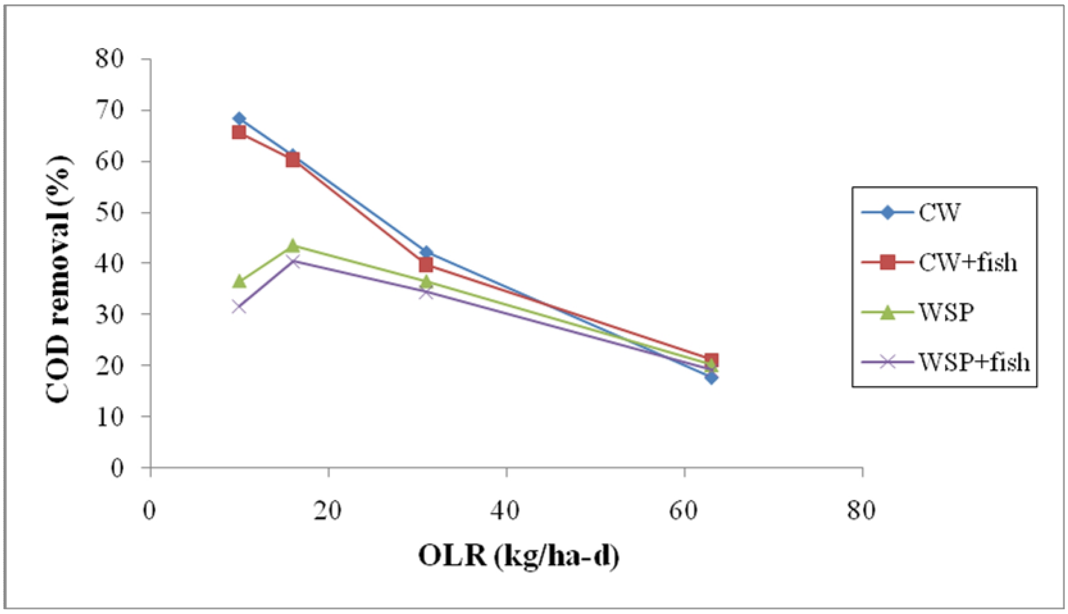


Figure 4.3 The COD removal efficiencies versus OLR of CW, CW with fish, WSP, and WSP with fish.

which NH_4^+ is converted to NO_3^-. The oxygen required for nitrification originated from oxygen aeration from the atmosphere and leakage from aquatic plant roots. Moreover, nitrogen is also taken up by plants, incorporated into plant biomass and algal biomass. However, waters flowing through the wetlands have a pH of near neutrality, and thus the significantly losses of ammonia by volatilization would not be expected. By the same way, ammonia in WSP or maturation ponds, is incorporated into new algal biomass And also the decreasing in ammonia concentrations in WSP were probably by the process of volatilization because pH of WSP systems were quite high (7.5-10) and some of the ammonia will leave the pond by volatilization process at higher pH (pH>8.3). The reason might be algae which grew in WSP because a higher pH in the WSP than that in the SFW due to high photosynthetic activity (Sajn Slak, Bulc, and Vrhovsek, 2005). To compare the mass removal rates of ammonia nitrogen as can be seen in Figure 4.4 with the BOD and TSS removal efficiencies, it was found that they demonstrates the similar phenomenon trend among them. Ammonia can be removed well resulting at OLR of 16 and 31 kg BOD/ha-d for WSP both with and without fish. At these OLR, BOD and TSS removal efficiencies of WSP were high that means the algal biomass concentrations in the ponds appeared in the smaller amount than that of others OLR. It might be that DO concentrations in those ponds were enough to motivate the ammonia removal processes that bring about high mass removal rates. On the other hand, Chongrak Polprasert (1996) stated that "introducing fish ponds in series with WSP or the culture of fish in WSP was found to reduce algal and bacterial concentrations to a considerable extent when herbivorous fish species (tilapia and silver carp) were used". According to this reason, tilapia fish reared into WSP units in this study would help to improve ammonia treatment performance by reducing algal concentrations in the ponds.

4.1.6 Orthophosphate (o-PO_4^{3-})

Phosphorus (P) is an important nutrient in the wetland system because it is required for plant growth but an excess amount of P in the water-body is among the principal constituents of concern in wastewater because of it role as a cause of eutrophication. The main processes of P removal are plant uptake, adsorption, precipitation and complexation. Adsorption and precipitation reactions are the major removal pathways when the hydraulic retention time is longer. However, in many cases, wetlands do not provide the high level of long-term removal for P because wetlands are capable of adsorping and absorbing P loadings until the capacity of the soils and plant growth are saturated and then it will release back to the systems after plant death.

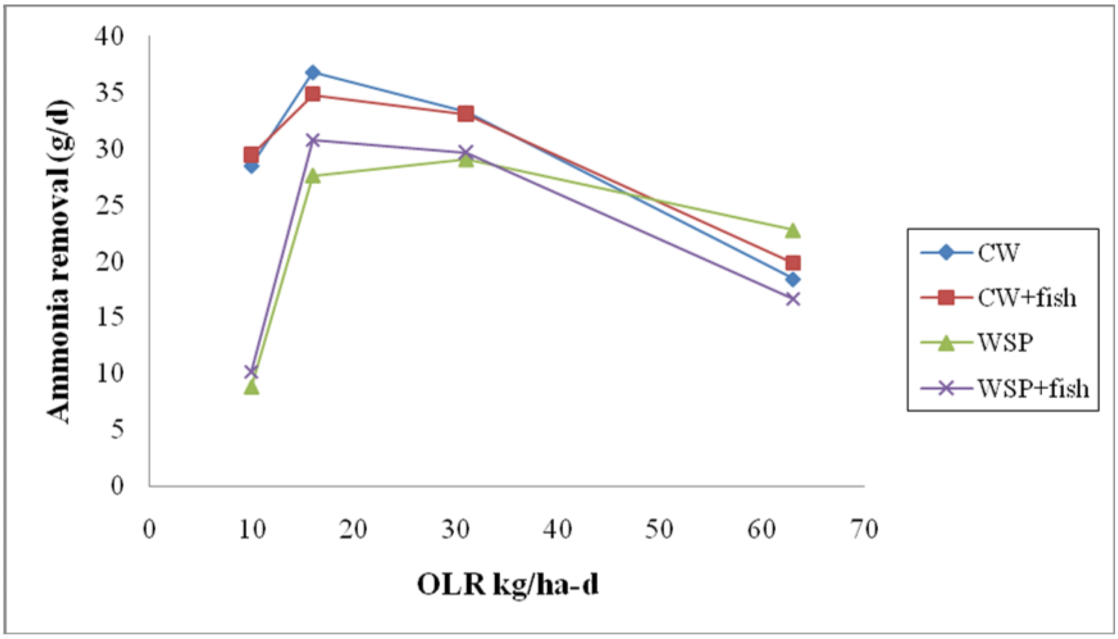


Figure 4.4 Ammonia nitrogen removal versus OLR of CW, CW with fish, WSP, and WSP with fish.

Orthophosphate is the predominant inorganic form of P in surface waters. It is readily utilized by aquatic organisms. Plant and soil can accumulate this P form easily because organic forms of P are generally not biologically or chemically reactive in wetlands. Moreover, particulate P is also broken down to inorganic form before being removed from the systems. The main o-PO_4^{3-} removal mechanisms in FWS systems are soil sorption and plant uptake.

Then the data of influent and effluent of o-PO_4^{3-} used to determine the removal efficiencies of CW and WSP with and without fish are presented in Appendix A. The influent wastewater was fluctuated in the range of 3.03-5.75 mg/L and 3.13-6.51 mg/L for CW and WSP systems, respectively. Then the effluent concentrations were ranged between 0.47-2.80 mg/L, 0.35-2.81 mg/L, 2.27-3.24 mg/L, and 2.19-3.40 mg/L for CW with fish, CW without fish, WSP with fish, and

WSP without fish, respectively. The average removal efficiencies were in the range of 43.59-87.26%, 41.83-92.22%, 8.82-50.95%, and 8.20-52.79% during the four experimental runs for CW with fish, CW without fish, WSP with fish, and WSP without fish, respectively.

The removal efficiencies of o-PO_4^{3-} were highest at Run 2 (16 kg BOD/ha-d) for both CW and WSP systems and the removal rates tend to reduce with the OLR increasing. The removal efficiencies resulting in different OLR are illustrated in Figure 4.5. For CW systems, the removal efficiencies were significantly higher ($P<0.05$) in Run 1 and Run 2 than that in Run 3 and Run 4 in both CW with and without fish. Moreover, the o-PO_4^{3-} removal efficiencies in Run 3 were also significantly higher ($P<0.05$) than that in Run 4. However, o-PO_4^{3-} removals in Run 1 were not different significantly ($P>0.05$) from Run 2 both the systems with and without fish.

The high removal efficiencies may be due to the o-PO_4^{3-} uptake by the macrophytes in the systems, which required a long hydraulic retention time. Furthermore, Gearheart (1993) has revealed that the wetlands reduced the concentration of o-PO_4^{3-} through plant uptake, suspended solids adsorption and settling, and sediment adsorption. Moreover, the difference concentrations of o-PO_4^{3-} effluent between CW and WSP systems would be the process from the soil adsorption.

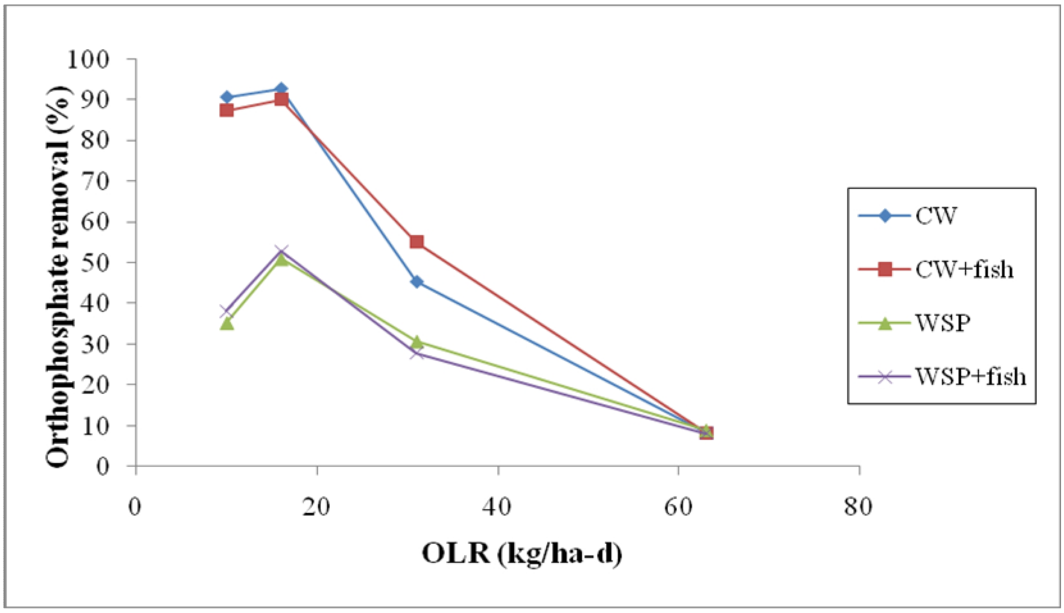


Figure 4.5 The o-PO_4^{3-} removal efficiencies versus OLR of CW, CW with fish, WSP, and WSP with fish.

4.2 Plant production

4.2.1 Plant height

The plant stems filtered and reduced some particles in water. When they died, they acted as net that filtered some filthy. They reduced flow rate inflow and they could induce particles accumulated or precipitated in the systems. Plant heights were measured to investigate plant growth in the differences of organic loading rate (10, 16, 31, 63 kg BOD/ha-d) and between constructed wetland with and without fish. Papyrus were planted in the constructed wetlands and cut down to 0.6 m above ground before starting the experimental run. Then they were measured every 10 days as depicted in Table 4.1.

The plant heights in each experimental run were not difference between wetland with and without fish. Furthermore, in each measurement period, the data of

Table 4.1 Plant height of papyrus in four runs of CW with and without fish.

Time (day)	Plant height (cm)							
	Run1		Run 2		Run 3		Run 4	
	CW	CW with fish	CW	CW with fish	CW	CW with fish	CW	CW with fish
0	0	0	0	0	0	0	0	0
10	63.78	61.95	63.72	65.58	70.69	71.83	76.33	77.58
20	110.7	103.1	117.8	120.1	127.2	128.8	134.9	137.4
30	132.3	128.8	136.4	138.8	148.9	150.2	152.0	155.1
40	150.0	148.4	165.8	169.5	160.8	164.4	169.6	173.3
50	165.6	165.3	176.9	178.9	170.5	169.7	180.4	182.7
60	186.4	185.8	188.5	190.0	181.4	180.8	191.4	191.4

plant height were found to be equal in all runs. It can be explained that the plant heights are not influenced by the OLR or retention time. Their height of papyrus initially increased rapidly and then decreased the growth rate in the end of run period.

4.2.2 Plant biomass and productivity

Measurements of standing biomass and above-ground productivity were made in quadrates of 0.5 m×0.5 m after the end of each experimental run. The plant biomass of CW with and without fish are ranged from 2280-2849 g dry weight/m^2 and 2341-3115 g dry weight/m^2, respectively. The plant biomass and productivity including the productivity of each part of papyrus (culm and umbel) are summarized in Table 4.2.

The umbel biomass was higher than that of the culm at the culm: umbel biomass ratio of 1:1.5. Umbels serve also as main photosynthetic surface of this plant. The aerial biomass of the papyrus in this study was comparatively lower to previous studies because of the shorter planting duration and low-strength wastewater (Muthuri et al., 1989 and Chale, 1987). However, differences in aerial biomass of papyrus in various sites have been attributed to prevailing climatic conditions. In addition, papyrus has its proportion of its biomass allocated to the aerial biomass, in which the largest proportion is in umbels but is not the same as the previous studies. The reason should be about the age of the papyrus in this study was younger than in the others. Older culms trend to be bigger than younger ones because papyrus is perennial emergent macrophyte that has an annual cycle of growth. High aerial primary production indicates that, less amount of carbohydrate is assimilated to the rhizomes, hence the living culms and umbel acted as storage organs, the function which is normally for rhizome. It should be noted that, in the tropical wetland that has solar radiation at least 12 h a day round the year, water and nutrient availability are not the limiting growth factors in this ecosystem. Finally, plant biomass and productivity are related to nutrients removal capacity in CWs, as is evidenced that plant growth is increased in proportional to the nutrients removal efficiency.

From the results of plant biomass, the relationship between plant biomass versus time of CW with and without fish were plotted as illustrated in Figure 4.6 and 4.7, respectively. This plant growth has a tendency to be in the transitional

Table 4.2 Biomass and primary productivity of papyrus in each constructed wetland units.

Run	Plant biomass (g dry weight/ m^2)		Plant productivity (g dry weight/m^2-d)		Culm productivity (g dry weight/m^2-d)		Umbel productivity (g dry weight/m^2-d)	
	CW	CW with fish	CW	CW with fish	CW	CW with fish	CW	CW with fish
1	2341	2486	39.02	41.44	15.99	16.57	23.03	24.87
2	2359	2758	39.32	45.97	14.28	16.43	25.04	29.54
3	2538	2280	42.30	38.00	15.87	13.64	26.43	24.36
4	3115	2849	51.91	47.49	20.26	17.43	31.65	30.06

phase of sigmoid curve for normal population growth rate so that the papyrus growth rate was formulated, according to equation (4.1).

$$m_t = m_u\left(1 - e^{-kt}\right) \tag{4.1}$$

Where:

m_t = biomass at time (g dry weight/ m^2)

m_u = ultimate biomass (g dry weight/ m^2)

k = rate constant (1/d)

t = time (d)

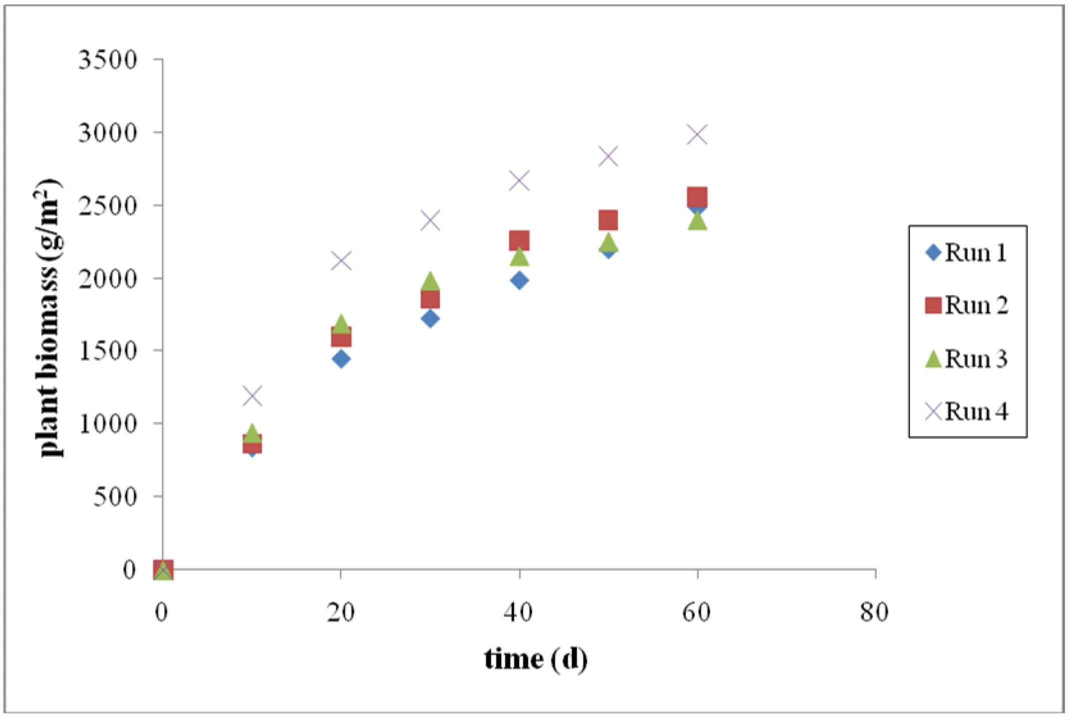


Figure 4.6 The progressive growth of papyrus in each CW units with fish.

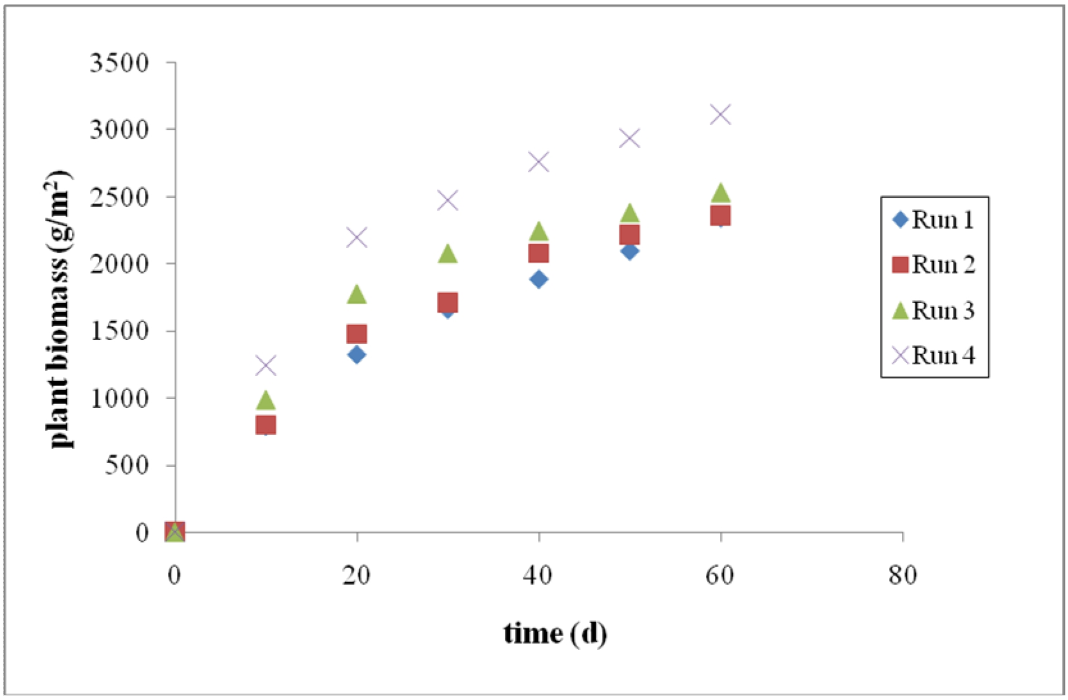


Figure 4.7 The progressive growth of papyrus in each CW units without fish.

From Figure 4.6 and 4.7, slopes along the curves were determined and plotted as shown in Figure 4.8 and 4.9 for CW with and without fish, respectively. They showed that the optimum period for harvesting can be found to be 51-60 days for CW with fish and 41-50 days for CW without fish. At the optimum point, the growth rate of the plant is lowest. Subsequently, further allowance for plant growth is useless and, in the commercial sense, the opportunity for exploitation of the value added material is lost. Thus, papyrus in CW systems should be harvested between 41-60 days.

4.2.3 Nutrient removal

Nutrient concentrations were calculated on a mass per unit mass dry weight basis. Concentrations of nitrogen in plant material were presented in the umbels about 8.81 g/m^2, 5.63 g/m^2, 6.04 g/m^2 and 9.68 g/m^2 of CW without fish for Run 1, Run 2, Run 3 and Run 4, respectively. For CW with fish, the umbel nitrogen uptake of papyrus were 4.00 g/m^2, 6.66 g/m^2, 4.65 g/m^2 and 8.52 g/m^2 for Run 1, Run 2, Run 3 and Run 4, respectively. Moreover, culm can assimilate lower nitrogen than umbel. The nitrogen in culm parts were 3.11 and 2.40 g/m^2, 4.27 and 4.96 g/m^2, 3.98 and 2.82 g/m^2, and 5.97 and 4.88 g/m^2 of CW without fish and CW with fish for Run 1, Run 2, Run 3 and Run 4, respectively. The umbel and culm N plant uptake are shown in Appendix B.

From the results of phosphorus concentrations in the wastewater, the highest concentration was found in the umbel. Concentrations of phosphorus in umbel were 13.38 and 15.24 g/m^2, 11.67 and 14.32 g/m^2, 14.62 and 17.43 g/m^2, and 18.08 and 17.41 g/m^2 for CW without fish and CW with fish for Run 1, Run 2, Run 3, and Run 4, respectively. The culm phosphorus uptakes were 7.53 and 7.64 g/m^2, 5.83 and

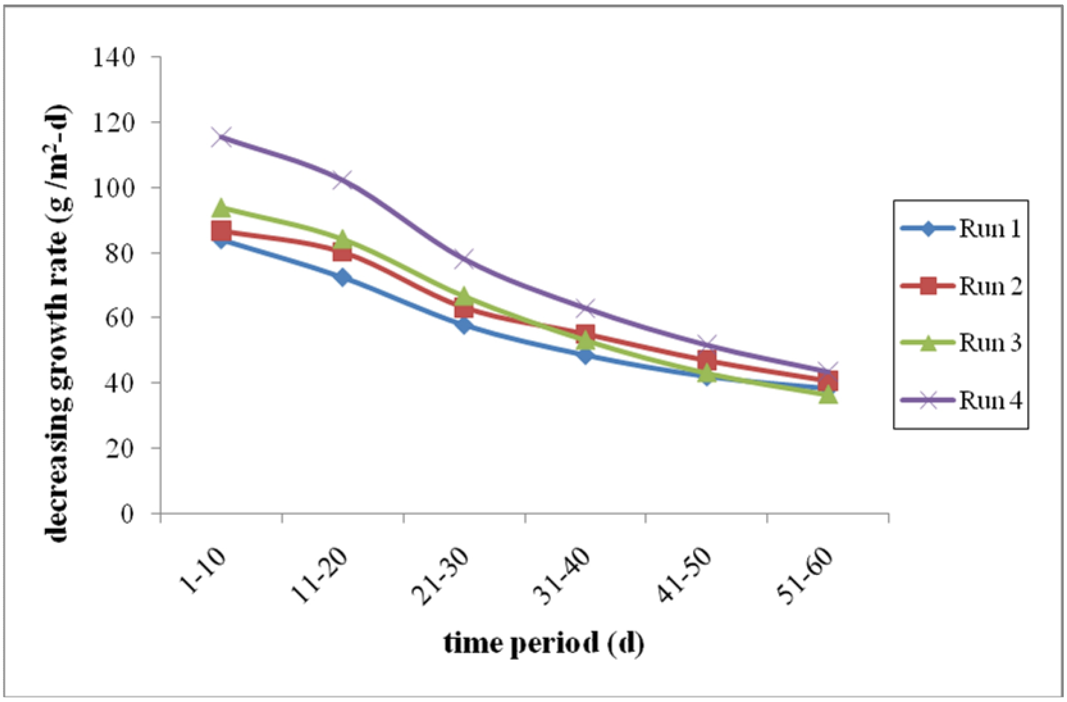


Figure 4.8 The decreasing growth rates of papyrus in CW with fish.

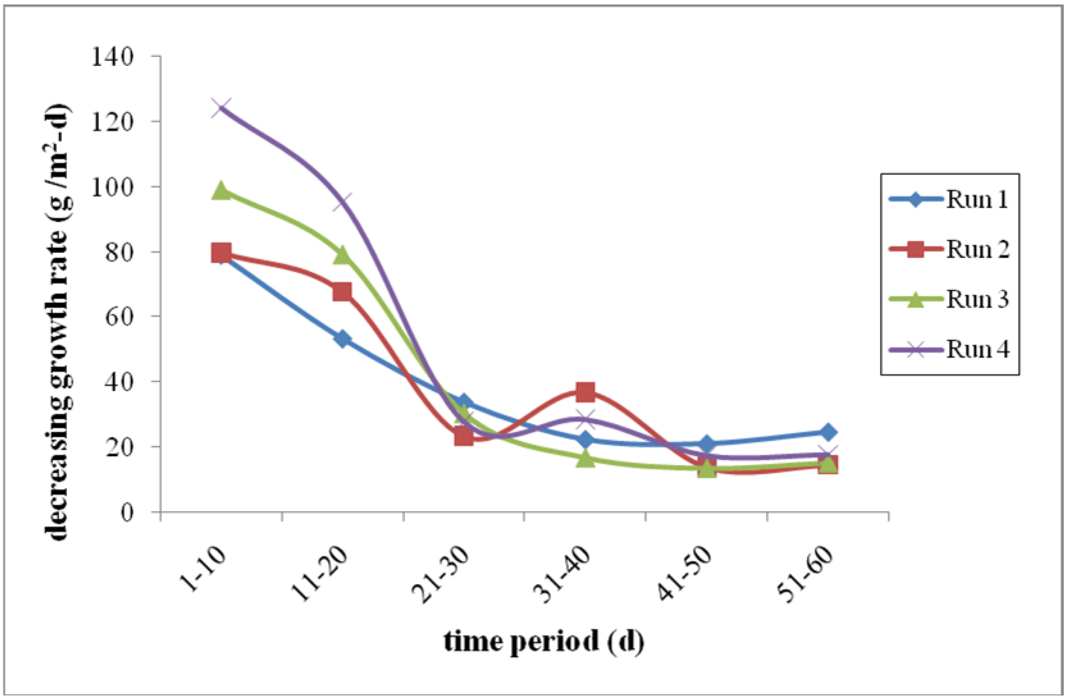


Figure 4.9 The decreasing growth rates of papyrus in CW without fish.

6.87 g/m^2, 6.12 and 5.35 g/m^2, and 9.27 and 7.46 g/m^2 for CW without fish and CW with fish for Run 1, Run 2, Run 3, and Run 4, respectively. The umbel and culm N plant uptake are shown in Appendix B.

The papyrus umbel and culm of CW took up 1.28 and 0.45%, 0.68 and 0.52%, 0.52 and 0.34%, and 0.48 and 0.30% of nitrogen load for Run 1, Run 2, Run 3, and Run 4, respectively. Furthermore for the CW with fish, the umbel and culm of papyrus could uptake nitrogen 0.58 and 0.35%, 0.81 and 0.60%, 0.40 and 0.24%, and 0.42 and 0.24% for Run 1, Run 2, Run 3, and Run 4, respectively.

The uptakes of phosphorus in umbel and culm of CW were 6.85 and 3.85% for Run 1, 5.51 and 2.75% for Run 2, 5.58 and 2.34% for Run 3, and 3.13 and 1.60% for Run 4, respectively. Moreover, the papyrus umbel and culm of CW with fish took up 7.80 and 3.91% for Run 1, 6.76 and 3.24% for Run 2, 6.65 and 2.04% for Run 3, and 3.01 and 1.29% for Run 4, respectively.

The results showed that the highest nutrients concentrations both N and P were found in the umbel because it serves as the main photosynthetic organ. The photosynthetic organs and the inflorescences generally have higher nutrient content than other organs. Confirming this for papyrus, highest concentration of nitrogen and phosphorus were found in the umbel. The rate of nutrients accumulation depends on its availability, which consequently determines the rate of biomass production. The potential rate of nutrient uptake by plant is limited by its net productivity (growth rate) and the concentration of nutrients in the plant tissue. Therefore, desirable traits of a plant used for nutrient assimilation and storage would include rapid growth, high tissue nutrient content, and the capability to attain a high standing crop. Papyrus is one of the most productive plants in the world. It has a floating mat that incorporates a large amount of nutrients in its organs. The roots of papyrus harbor nitrogen fixing organisms which provide nitrogen in a form that the plant can take up as nutrient.

Phosphorus storage in aboveground biomass of emergent macrophytes is usually short-term and the only significant form of inorganic phosphorus in the CW is orthophosphate which is the predominant form of phosphorus in this study.

4.3 Fish production

Tilapia was selected for rearing in the CW for 2 months during the experimental runs. All male were introduced with the stock density of 4 capita/m^2 and their age is about 3 months. They were measured the weight every 15 days and their average weights and survival rates in each ponds for four experimental runs are summarized in Table 4.3 and 4.4.

In the CW units, the survival rates are in the range of 75-100% which were higher than in the WSP that are ranged from 29-75%. Wetlands can improve water quality suitable for rearing fish. The emergent plant in CW shades the water surface and reduces wind-induced turbulence in the water flowing through the systems so that wetlands may serves as shelter and cover for fish. The sunlight was reduced from plants, preventing growth of algae cells in the CW, thereby keeping water clear. Furthermore, aquatic plants serve as the food source for herbivorous fish and they pump oxygen to their root zones that are used by fish and bacterial cells in the treatment units. For WSP, the survival rates of Run 1 and 2 are low because the water surfaces were covered by the algae so that oxygen cannot pass through the water and then fish is lack of oxygen.

Table 4.3 The average weights and survival rates of Tilapia in CW with fish.

Run	Average initial weight (g)	Average last weight (g)	Survival Rate (%)	Productivity (g/m^2)
1	15.42	56.48	87.50	143.7
2	14.75	61.17	100.0	185.7
3	15.50	64.00	83.33	161.7
4	15.62	64.11	75.00	145.5

Table 4.4 The average weights and survival rates of Tilapia in WSP with fish.

Run	Average initial weight (g)	Average last weight (g)	Survival Rate (%)	Productivity (g/m^2)
1	15.33	48.29	29.17	38.45
2	14.75	52.31	54.17	81.39
3	15.71	56.28	75.00	121.7
4	15.79	56.38	66.67	108.3

The average weights of fish in CW are among 56-65 g per capita and 48-57 g per capita for WSP units. Its weight is lower than the commercial fish weight that at 5-month age, its weight should be around 200-300 g because of fodder and fertilizers (Chumkaew, www, 2005). Furthermore, the production in extensive pond systems is based on the natural productivity of the pond and solar radiation. The net weight and daily weight gain per fish were among 40-50 g and 0.6-0.8 g/d for CWs, respectively.

While for the WSPs, the net weight and daily weight gain per fish can be estimated in the range of 33-41 g and 0.5-0.7 g/d, respectively. These daily weight gain values were comparable with the tilapia fish in the cages in the Seyhan Dam Lake at Turkey about 0.556±0.005 g per fish/d (Dikel et al., 2005). However, the daily weight gain in this experiment was quite lower than that the daily weight gain in commercial purpose because fish increased its weight at 4.9-5.86 g per fish/d (Department of agricultural extension, www). The reason would be food feeding for fish in the systems because fish in CW and WSP systems might consume food from the nature such as algal cells, bacterial cells and aquatic plant. In the other hand, in commercial purpose, fish were fed with fodder and fertilizers which accelerate the fish growth rate. Fish production in CW and WSP were quite different in Run 1 and Run 2 and the cumulative biomass during the experimental period in each run of CW and WSP with fish are shown in Figure 4.10 and 4.11.

4.4 Energy capturing efficiency

The energy content of papyrus was determined by using bomb calorimeter. Each part of the above-ground plant (culm and umbel) used in CW units of the experimental run 1 were analyzed for the calorific value. Each system was operated with two units running in duplicate so as to ensure the accuracy of the data obtained. The sub-units were operated as follows: CW1/1 and CW1/2 were papyrus only; CW 2/1 and CW 2/2 were papyrus with fish. The average energy content of culms, umbels and total above-ground parts are to be in the range reported of 15.08 to 16.95 MJ/kg, 16.71 to 18.30 MJ/kg and 16.18 to 17.48 MJ/kg, respectively. The results are shown in Appendix B.

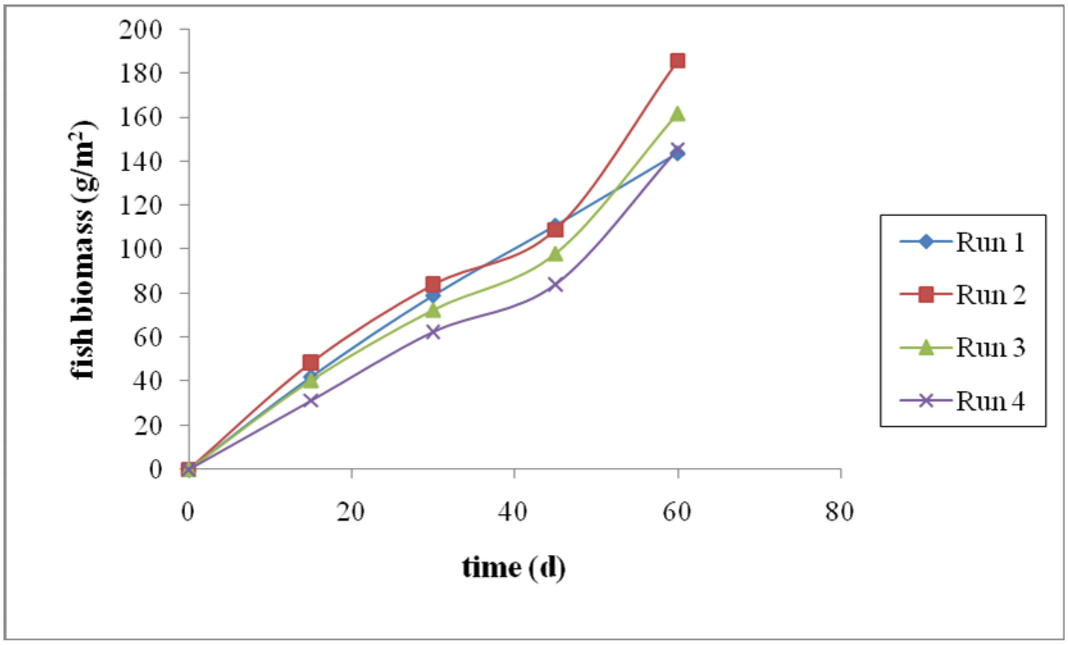


Figure 4.10 The increment biomass during the experimental period in each run of CW.

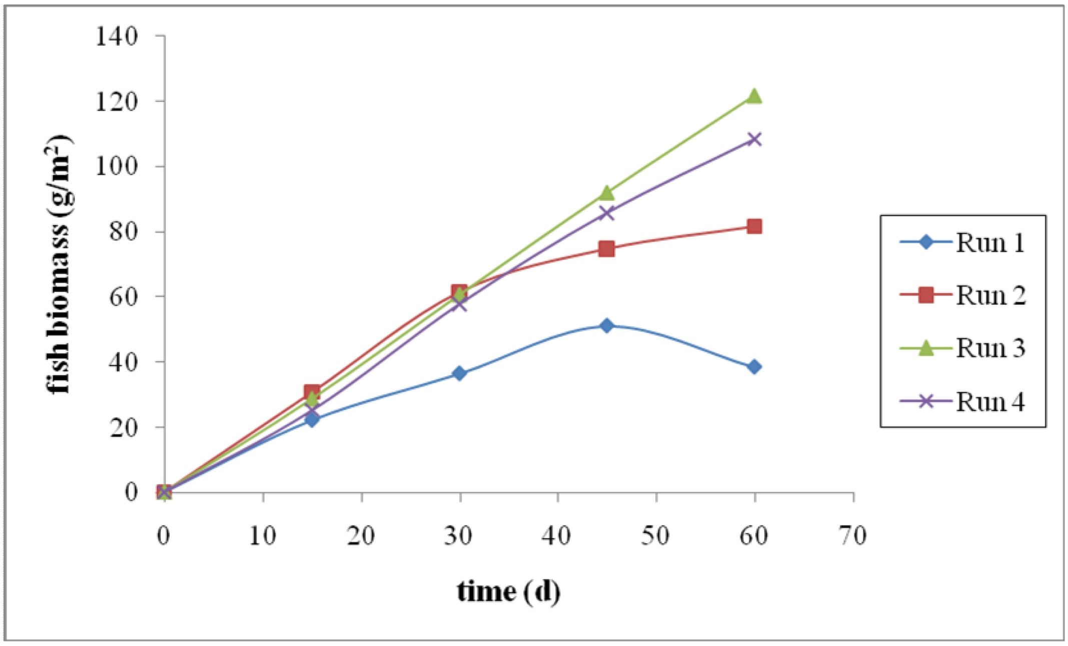
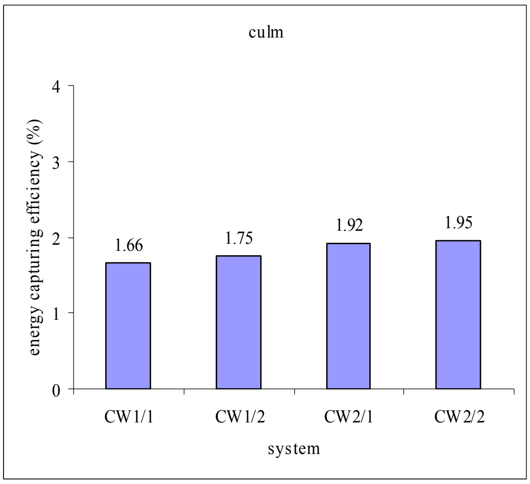


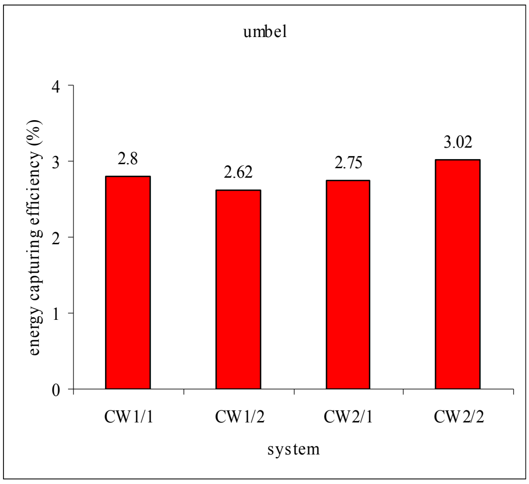
Figure 4.11 The increment biomass during the experimental period in each run of WSP.

Long et al. (1992) stated that, for most plant material, the energy content per unit organic biomass will fall within the range 17-20 MJ/kg which is the same as the results from Jenkins and Ebeling (1985) that reported the heating values of samples from six categories: field crop residues, orchard prunings, vineyard prunings, food and fiber processing wastes, forest residues and energy crops. Primary productivity in each part of papyrus was used to determine the energy capturing efficiencies by comparing with the average solar radiation worldwide equal to 168 W/m^2 (Masters, 1998). Solar energy capturing efficiencies of papyrus are in the range of 1.66-1.95% and 2.62-3.02% of culms and umbels, respectively. Moreover, the efficiencies of total above ground part are in the range of 4.22-4.98%. The energy capturing efficiencies of papyrus are shown in Figure 4.12. Umbels represented the higher energy capturing efficiency parts than culms because they serve also as main photosynthetic surface (Jones and Humphries, 2002). The results shows that this plant likes to grow in full sun so that it can capture more energy from the sun and transform into the plant production and it has a high photosynthetic and productive potential due to the presence of C_4 photosynthesis in spite of the fact that it grows in a wetland ecosystem, which appears unlikely habitat for C_4 species (Jones and Milburn, 1978).

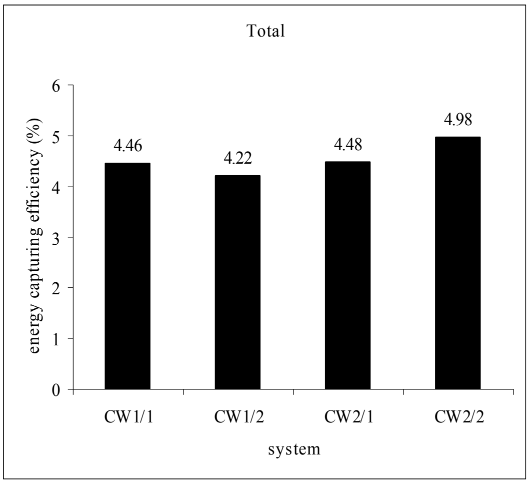
4.5 Thermodynamic model development

Conceptual model that encompasses the relationship among aquatic macrophyte, fish, and wastewater in the free-water constructed wetland treating low-strength wastewater, was developed by using the thermodynamic concept as energy model.





(a) (b)



(c)

Figure 4.12 Energy capturing efficiencies of papyrus in each CW (a) culm (b) umbel and (c) total .

From the thermodynamic point of view, an ecosystem is a typical open system. In this study, CW was defined as the open system in thermodynamic which is heat, work and matter can cross the boundary (Jørgensen and Svirezev, 2004). The techniques for measuring the production and activities in CW are based on the limitation of energy and their ability to use the energy for themselves and other systems. Solar energy is the main source of energy for the biological system as CW. And also because CW relies on metabolic processes supported by solar energy, it was necessary to use the evaluation method that could account for renewable resources such as sunlight, wind etc. So that the ecological input in any product or service can be measured by the equivalent solar energy embodied in it (Bakshi, 2000). All product and activities are transformed and stored forms of solar energy both directly and indirectly to make them. Thus, the thermodynamic concepts as emergy analysis was selected in this study because it is defined as the better quantifiable way of the ecosystem analysis.

4.5.1 Definition

The thermodynamic concepts of energy and emergy are useful for the analysis of ecological system as well as constructed wetland, and are discussed in this section. Definitions for several key words and concept are given next:

Energy comes in many forms and it is a scalar quantity that cannot be observed directly. It is commonly used as a state variable that is easy to calculate. However, it has many limited factors. The energy change of process is a measure of quantity only and it can be neither destroyed nor produced so that it is not suitable to use for describing the real process (Dincer and Rosen, 2007).

Emergy is the embodied energy which is later changed to emergy. Emergy is the energy (referenced to the ultimate solar source) needed to make components in systems at different network distances from boundary inputs. Since the ability to do work can be different from the different kinds of energy. Everything is expressed in solar energy equivalents. For example, sunlight, fuel, wastewater, etc. can be put in a common basis by expressing them all in the emjoules of solar energy that is required for each. The concept of emergy is a system that measure the growth production of its individual units and explain them in the term of energy. The unit of emergy has changed from the energy unit (Joules) into solar energy unit (solar emergy joules or solar emjoules or sej). Moreover, emergy flow can also be evaluated from the flow of matter or money units. If data are in grams or money units (rather than energy), emergy are calculated by multiplying be the material's specific emergy (sej/g) or by an emergy/current ratio, respectively (Odum and Peterson, 1996).

Transformity is the ratio which is obtained by dividing emergy required to make a product or service by the energy yielded in that product or service. For example, papyrus requires sunlight as well as other inputs that can be converted to the common basis as solar energy. The total solar energy needed to produce papyrus can be divided by the mass of the yield to create a transformity. If 300,000 solar emjoules were used to produce papyrus biomass about 3000 grams, the transformity of papyrus should be account as 100 sej per gram of papyrus. The units of transformities have dimensions of emergy/energy or common use as sej/J. In addition, Transformities are used to convert energies of different types to emergy of the same type. Transformities increase from left to right in the energy hierarchy diagrams. The solar transformity of the sunlight absorbed by the earth is 1.0 by definition (Odum and Peterson, 1996).

4.5.2 Constructed wetland simulation energy model

The energy diagram provides with the flow and storage values, is presented as Figure 4.13. The diagram emphasizes the relationship among aquatic plant, fish and wastewater for treating wastewater and added value in CW unit. Main energy contribution to CW is given, based on plant and then it transfer to produce fish production. Two main inputs concerned in this diagram, consisted of sunlight and wastewater. The outputs are plant production, fish production and treated wastewater. Moreover, sub-item in wastewater is considered as nitrogen, phosphorus and organic matter in which some amounts were used by plant and fish in the CW boundary. Similary, items and flows are arranged from left to right in order of their unit emergy. From left to right, items are concentrated, starting with the sun and wastewater, which are collected by aquatic plants and further collected into the bodies of fish in the CW unit. Afterward, the data of CW with fish in Run 2 were used as the values to calibrate the CW energy model. A description of flow pathway appearing along with the difference equations, calibration values, units of measurement and value of pathway coefficients (k) are shown in Appendix C, as well as the notes to those calculations.

Then k-values were used to validate the model by simulating with data from CW Run 1. Figure 4.14 demonstrates the Microsoft Excel sheet for simulating model with Run 1 data. This spreadsheet included with differential energy equation, coefficients values, overview energy diagram and simulated data by using 1-day as the time interval. The calculation depended on the trend of storage: increase, decrease or stable. The 60-day simulated cumulative storages in each items including with water, plant biomass, fish biomass, nitrogen, phosphorus and organic matter are depicted in Figure 4.15-4.20. The fish biomass and plant biomass picked up as

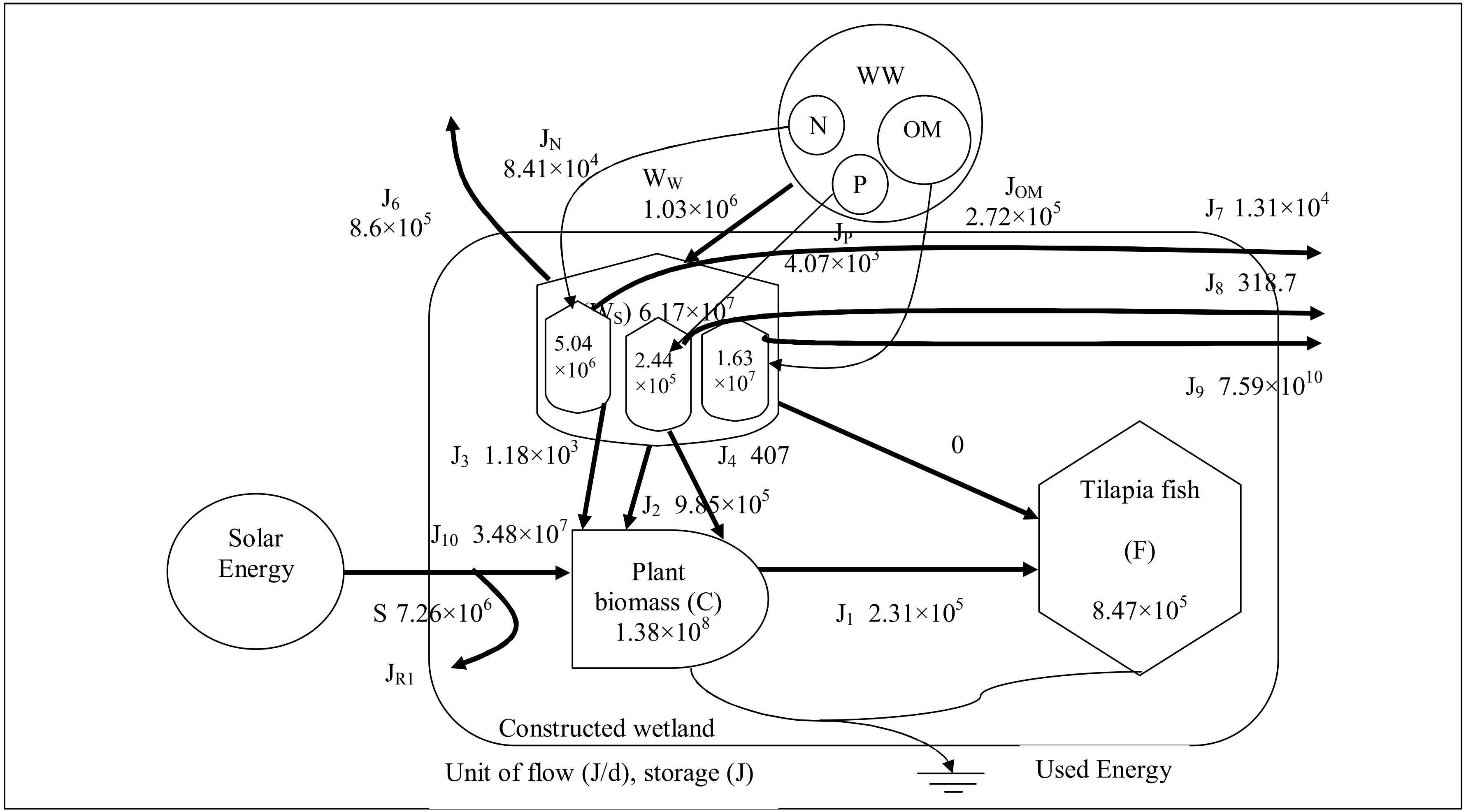


Figure 4.13 Calibration of energy and material flows of the constructed wetland.

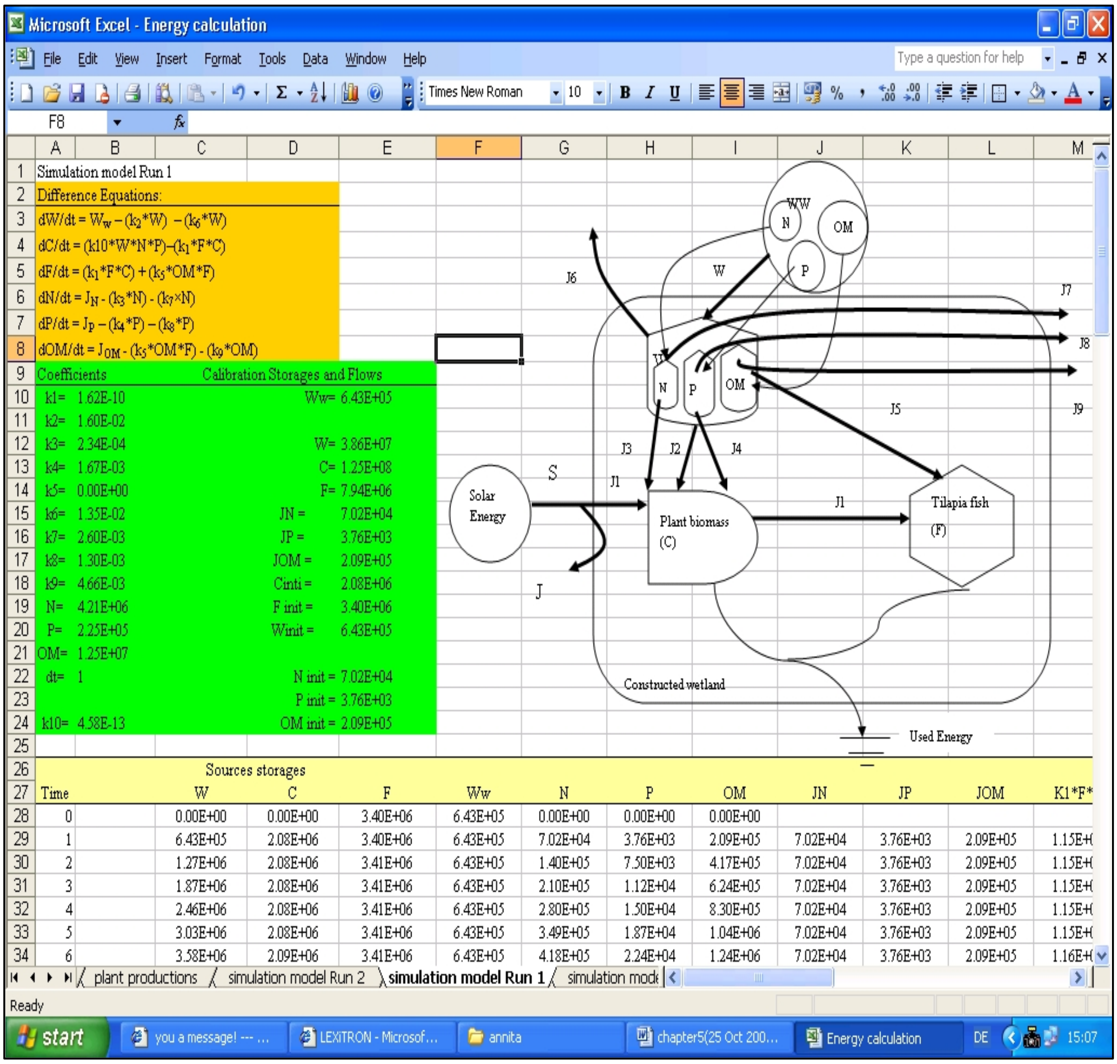


Figure 4.14 Simulation page's showing equations, coefficients, overview diagram and storages with the series of time.

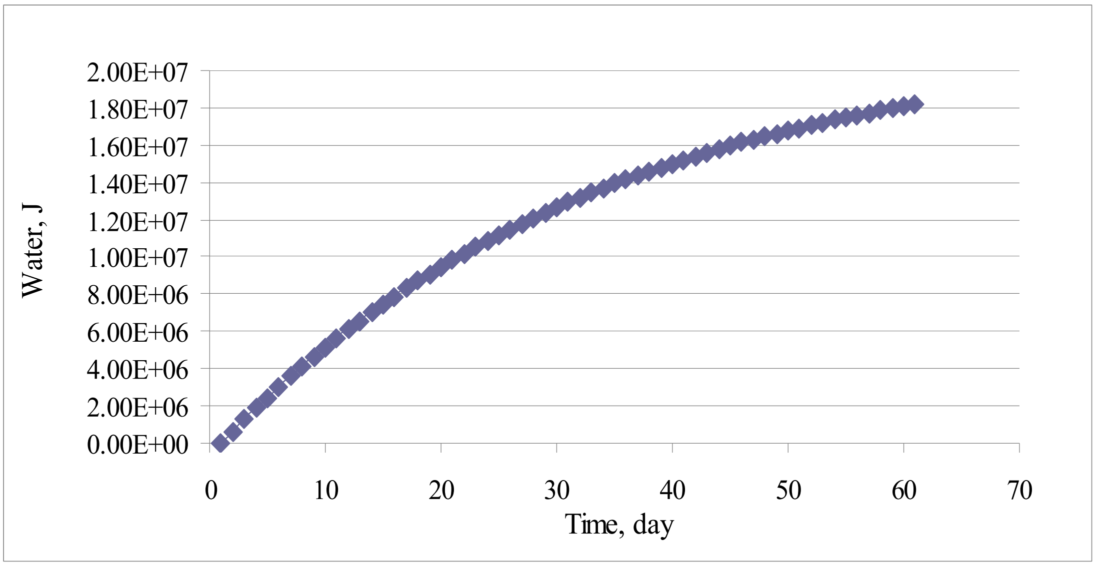


Figure 4.15 Simulation result of the water storage model with time series of CW Run 1.

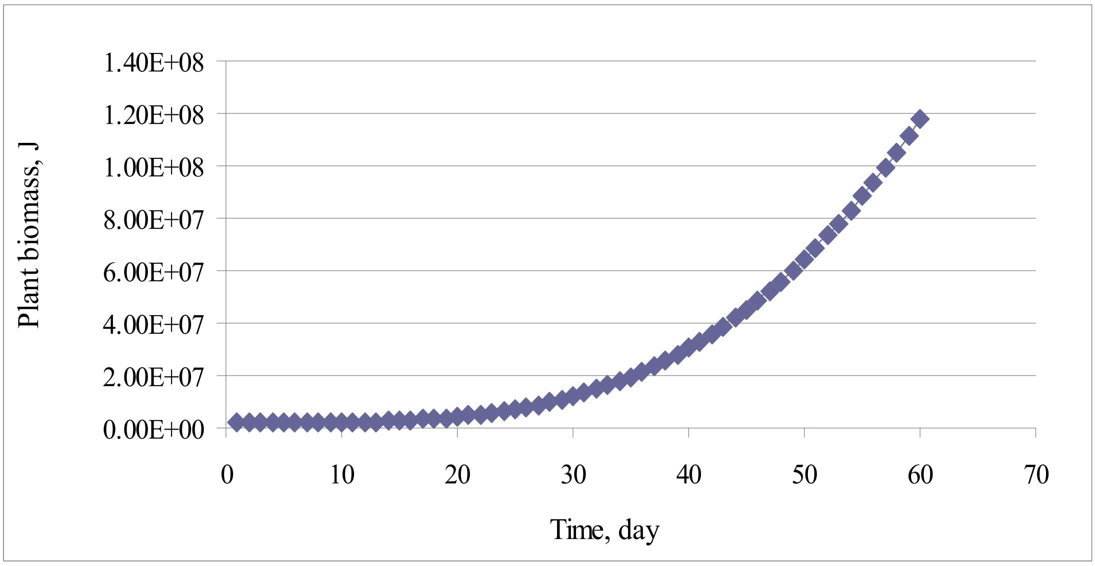


Figure 4.16 Simulation result of the plant biomass model with time series of CW Run 1.

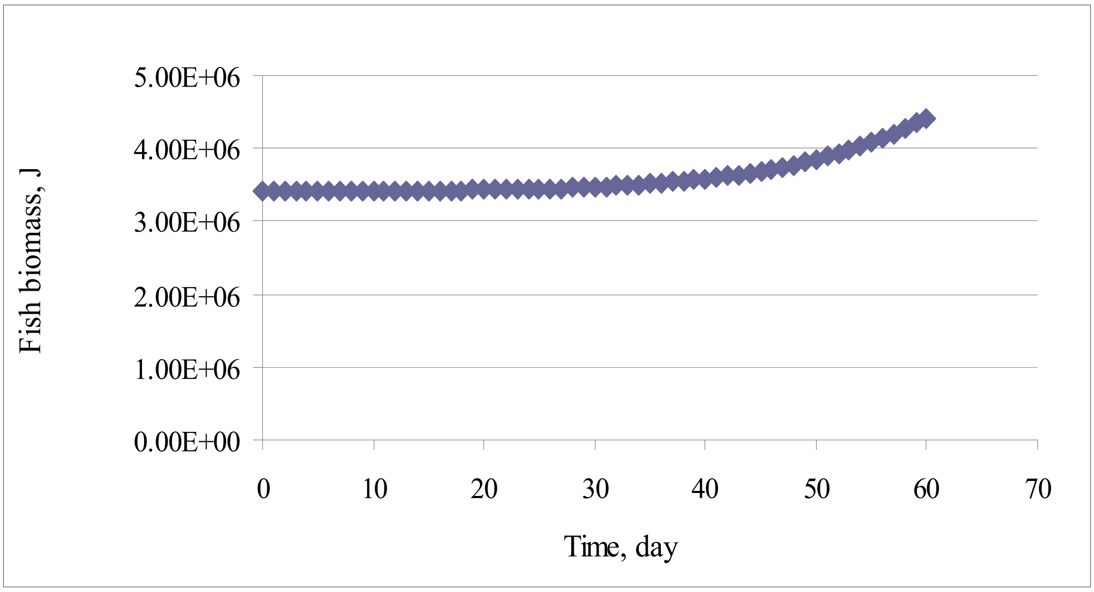


Figure 4.17 Simulation result of the fish biomass model with time series of CW Run 1.

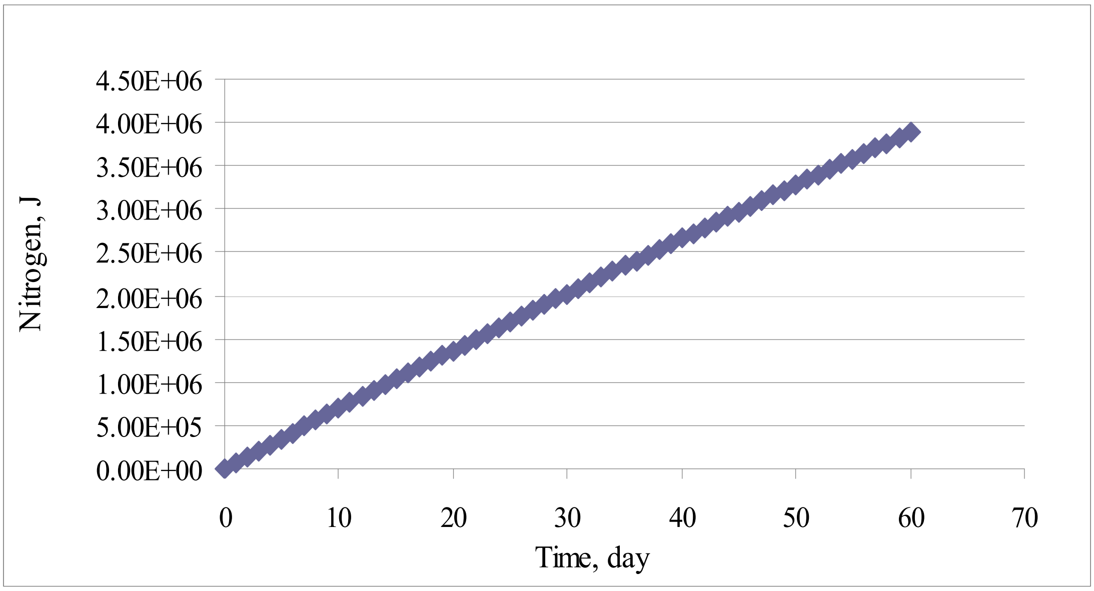


Figure 4.18 Simulation result of the nitrogen storage model with time series of CW Run 1.

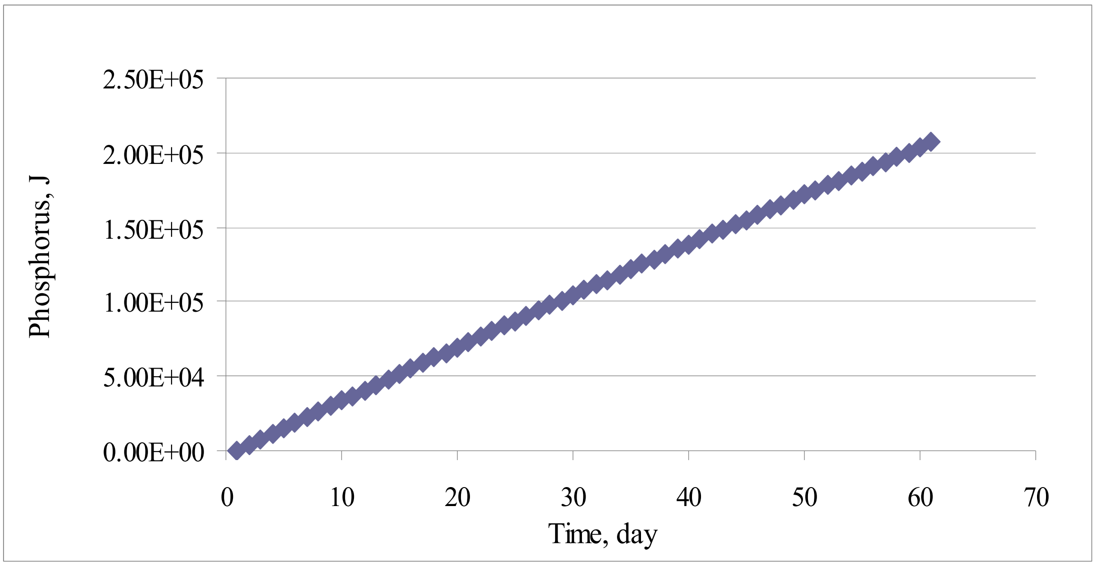


Figure 4.19 Simulation result of the phosphorus storage model with time series of CW Run 1.

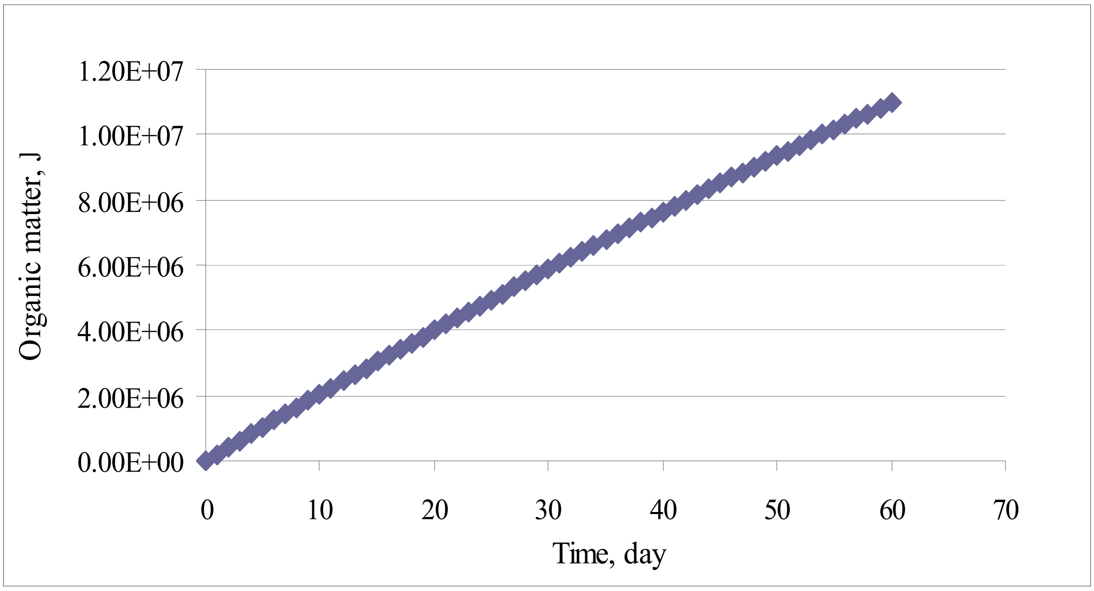


Figure 4.20 Simulation result of the organic matter storage model with time series of CW Run 1.

exponential growth which normally occurs as the normal population growth of living organism in ecosystem (Weatherley, Gill, and Casselman, 1987). Plant biomass storage was initial constant values and went up few amounts during 30-day period. Then the graph was steeper slope to reach the final value as 1.18×10^8 J. In addition, fish biomass speeded up slowly in the first 40 days and then grew up faster until it reached to 4.42×10^6 J in the 60-day trial period. The storage trends of fish and plant biomass were similarly the same because plant transferred energy to fish as the trophic chain since fish biomass depended on plant biomass in the equation. So that plant which can capture higher input energy is more useful in CW system both productivity and energy transfer point of view. In addition, nitrogen, phosphorus and organic matter graph pattern increase as the linear line because the average inflow and outflow were constant rate by the design criteria. Water storage involved with plant biomass because of the water used in plant photosynthetic reaction which made its different from the linear pattern as same as nutrients storage.

Afterward, the predicted and observed data were compared for the accuracy of the simulation model that they are the same or not. In this study, we focus on the plant and fish biomass production which their validation graph depicts in Figure 4.21 and 4.22, respectively. The overall data simulation showed that the correlation of plant accumulation biomass was not high (R^2=0.57) during the 60-day trial period. Nevertheless, after 20-day, the relationship between these data was quite good about R^2=0.9. The reason could be due to the nutrients uptake in the equation considered to values in the first nutrients than in further days. So that the predicted data were growing and contained small amounts of productivity since it could uptake lower constant rate all the times which is in fact in the initial days, plant biomass was

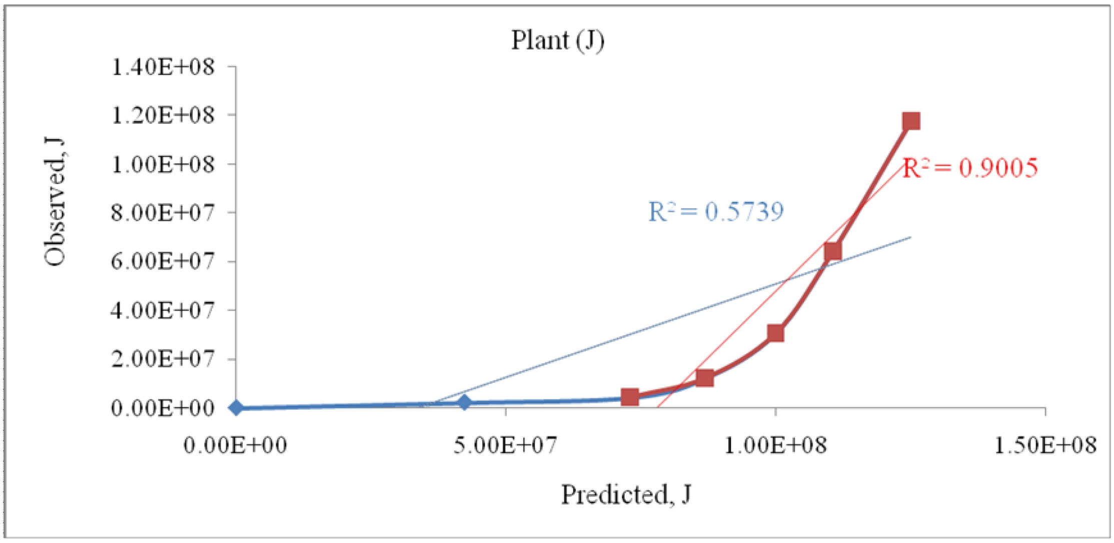


Figure 4.21 Correlation between predicted and observed plant accumulation in CW Run 1.

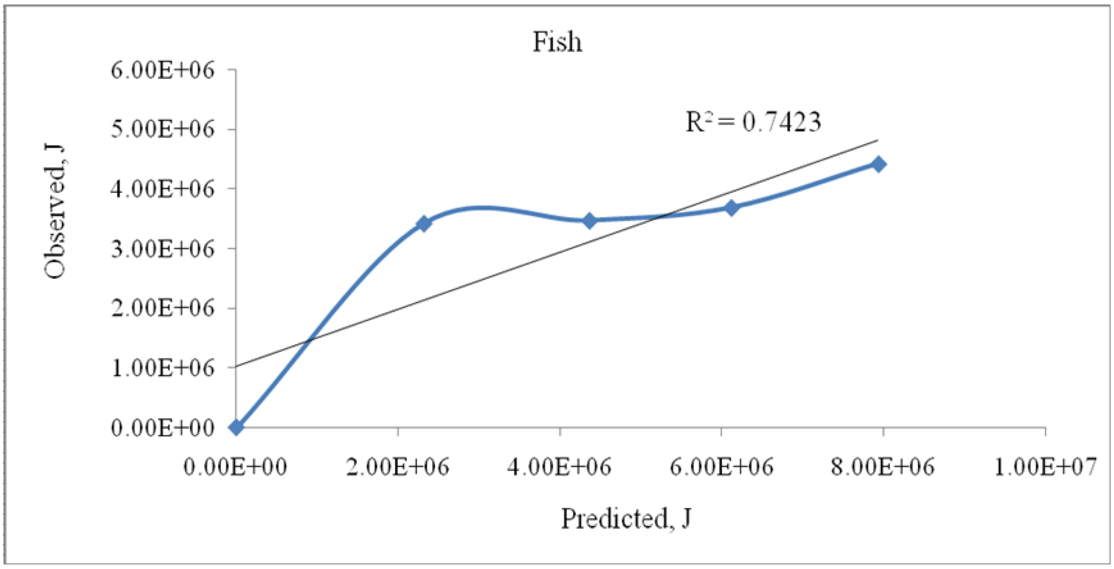


Figure 4.22 Correlation between predicted and observed fish accumulation in CW Run 1.

higher than the observed 20 days of experiment. Similarly, the correlation between predicted and observed data of fish biomass was good (R^2=0.74) that mean the energy equation of fish storage is suited to evaluate fish biomass in time series. However, the observed values had much greater energy storage than the predicted values. This could be due to organic matter assumed to be equal to zero in this energy model equation which is lower than in the real system. It means that organic matter is the other factor which is important in the energy transfer of fish growth that should consider in the energy equation.

This model can be applied to use with other units by changing fish species or plant species or wastewater type or wastewater concentrations. For example, catfish will be introduced instead of tilapia fish in further study and also emergent plant will be change from papyrus to cattail. Consequently, the time rate of change of fish biomass storage and plant biomass storage might be changed. Then the k-value will be newly determined and the new model would be simulated by using Microsoft Excel program. These equations can be used to calculate transformities for emergy evaluation when some parameters will be varied. Furthermore, the time rate of change of fish biomass and plant biomass could be used to compare growth rate and the optimum harvesting period of fish and plant among the different species. The graphs of time rate represent the energy flows and energy storages in the ecosystems. They help to manage the biomass production by adjusting the related parameter concentrations to produce the expected production. For example, increasing the nitrogen storage to 25%, 50%, and 90% of its steady state value will have a considerable effect on biomass storage growth. So that you can decide the target productivity as well as the suitable harvested period for the project can be evaluated.

4.5.3 Emergy evaluations of CW with fish in four experimental runs

The tables in Appendix C reveal the elements of production and substrates. They evaluated the solar emergy in CW calibration unit (Run 2) and then compared the emergy evaluation with the other units as well as waste stabilization ponds. Similarly, the energy calculation tables provided the data and the formulas of energy flows calculation in all experimental runs as the raw data for emergy analysis including in Appendix C. For the calculation of plant biomass and fish biomass, the data requires for converting it into energy form is energy content of this item. Likewise, other item needs the Gibbs free energy for transforming it as energy. All tables provide the transformities for sunlight, plant production, fish production, substrates, wastewater inflow, treated wastewater outflow and substrate outflows.

The total emergy inputs of CW wastewater treatment was the sum of wastewater and sunlight inputs that were 2.44×10^{12}, 3.91×10^{12}, 7.57×10^{12} and 1.54×10^{13} sej/d for CW corresponding with OLR of 10, 13, 31 and 63 kg BOD/ha-d, respectively. The main driving emergy input of CW in all experimental runs was wastewater input which was higher than that the sunlight input. Furthermore, the emergy of wastewater input varied for all experimental runs because they need more embodied energy in which OLR increased. The investigation suggests that the main energy used to produce biomass both plant and fish in the system is from wastewater. Nelson, Odum, Brown, and Alling (2001) stated that wastewater contains valuable nutrients and water which can be used to support productive wetland ecosystems from natural resource. However, solar energy is also important that could not be eliminated because it is the main factor for photosynthesis reaction. Likewise, the important indigenous nonrenewable resources, nitrogen, phosphorus and organic matter which are obtained from wastewater, are also important for the plant growth and fish growth. The main driving emergy for plant growth is nitrogen which was the highest emergy related to the important factor for plant growth in emergy evaluation table. The main emergy of treated wastewater is also from nitrogen outflow because this wastewater obtained from the dormitories which generated much of ammonia nitrogen as the dominated parameter. If we considered the overall items in the system boundary, the main driving emergy was wastewater in all units which should take into account as the main capital cost of CW treatment system.

Afterward, the emergy of plant and fish yields considered as the advantages from the CW units. The mean daily emergy of plant production (1.08×10^{10} sej/d) and fish production (2.17×10^{10} sej/d) of CW Run 2 accounted for 6.09 and 66.69% of total emergy cost in plant growth (emergy items 1+5+6 in Table C.3 of Appendix C) and fish growth (emergy items3+7 in Table C.3 of Appendix C), respectively. Table 4.9 shows the total emergy cost in plant and fish growth of CW in all runs. The total emergy of growth increased from Run 1 to Run 4 because the increasing organic matter and nutrients contained in the wastewater. Then the plant and fish production efficiencies in which how much energy can transform into the biomass, were evaluated by measuring the proportion between the emergy cost in plant and fish growth and their productivity. Furthermore, plant production efficiencies and fish production efficiencies in each experimental run were compared as shown in Figure 4.23 and 4.24, respectively.

The results reveal that plant production efficiencies were similar between Run 1 (6.55%) and Run 2 (6.09%). These efficiencies were nearly twice compared to Run 3 (3.58%) and 2.5 times of Run 4 (2.55%). It means that in Run 1

Table 4.9 Total emergy cost in plant and fish growth of CW in all runs.

Item	Run 1	Run 2	Run 3	Run 4
Total emergy cost in plant growth (sej/d)	1.48×10^{11}	1.77×10^{11}	2.49×10^{11}	4.35×10^{11}
Total emergy cost in fish growth (sej/d)	2.52×10^{10}	3.09×10^{10}	5.51×10^{10}	8.65×10^{10}

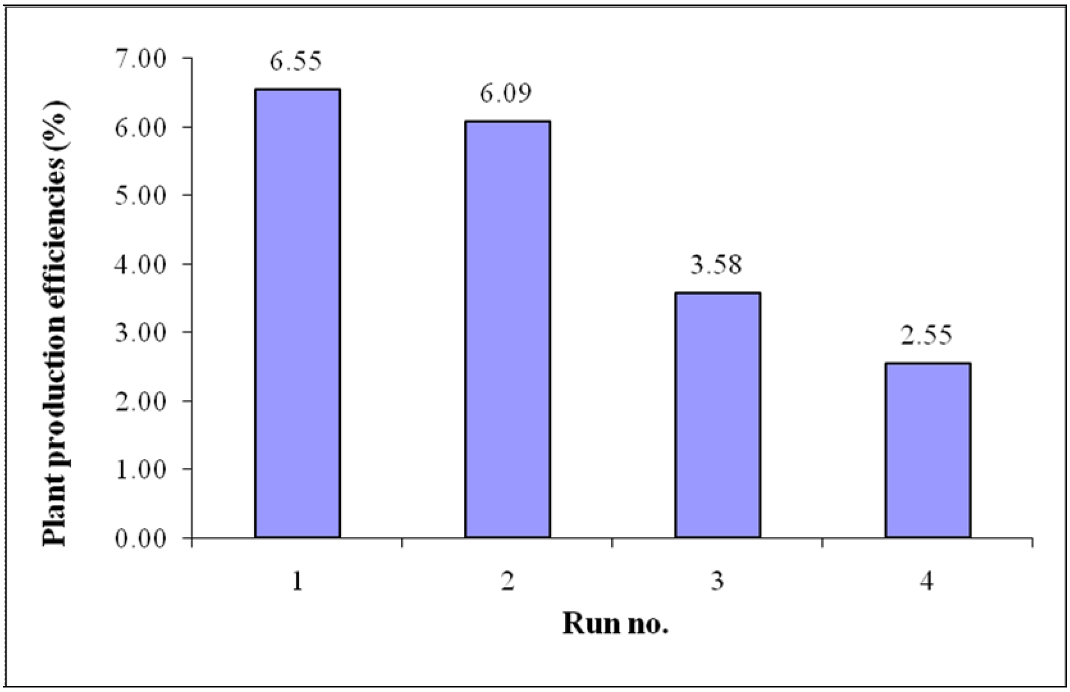


Figure 4.23 Plant production efficiencies of CW in each experimental run.

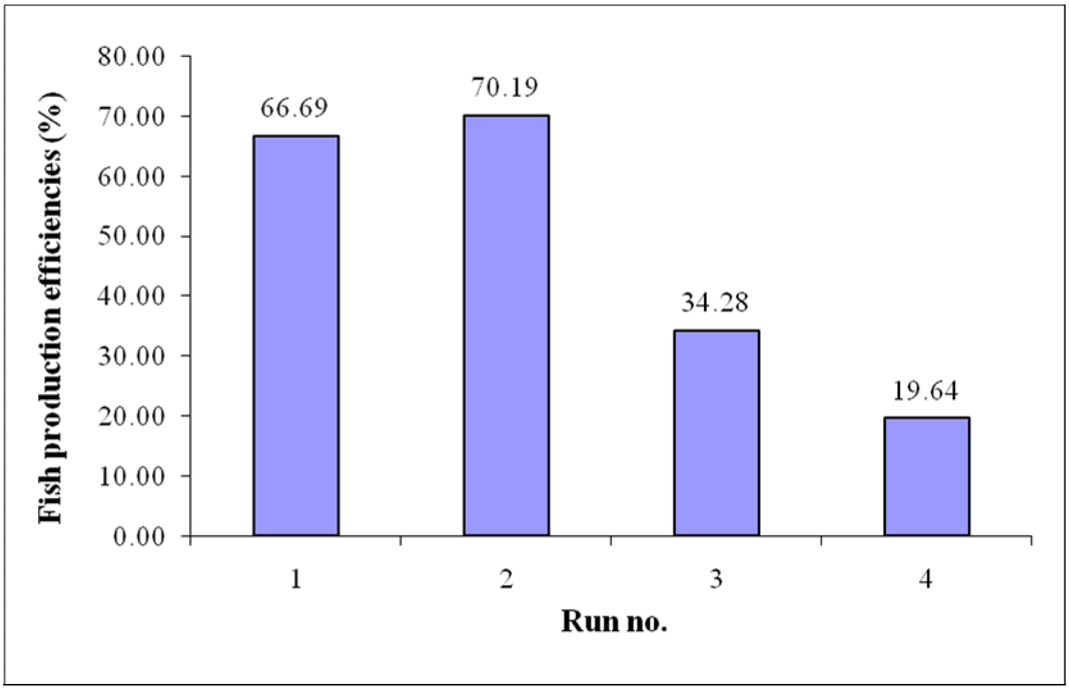


Figure 4.24 Fish production efficiencies of CW in each experimental run.

and Run 2, these energies from resources are appropriate amount for plant to convert them into plant biomass in the period of experimental time. In addition, if we compared plant efficiency for emergy concept with the energy capturing efficiency of CW Run 1 as mentioned in energy capturing efficiencies section. The plant were found to capture energy around 5% in the energy method calculation in previous which is nearly compared with emergy calculation in this chapter. As well as, fish production efficiencies, a comparison across experimental runs showed that in Run 2 had highest value (70.19%). However, it was closely similar with Run 1 (66.69%) as same as the result of plant production. As the same way, Run 1 was approximately twice fish production efficiency than Run 3 (34.28%) and nearly 2.5 times than Run 4 (19.64%). This result also indicated that for the small fish (3-month initial in this study), the emergy from plant biomass in Run 1 and Run 2 were suitable for the fish growth.

The wastewater treatment efficiency was the most important indicator for the purpose of waste treatment. Waste removal potential (EWRE) is the proportion of total emergy cost in waste treatment by waste removal (Zhou, Jiang, Chen, and Chen, 2009). For specific wastes as NH_3, PO_4^{3-} and organic matter (BOD), the corresponding Emergy waste removal potential (EWRP) are given in Table 4.5. To remove one gram of NH_3, PO_4^{3-} and organic matter (BOD) in wastewater from Run no. 2 needed emergy input of 1.18×10^{11}, 4.21×10^{11}, and 2.08×10^{11} sej/g, respectively. Compared with the other runs, EWRP varied with the emergy cost for the waste treatment for all runs. All parameters were used nearly emergy to remove one gram of waste. However, if we compared only EWRP of NH_3, it shows that Emergy used in Run 4 was quite different from other three runs. And the range of EWRP of BOD in all runs was narrowest than NH_3 and PO_4^{3-}. Constructed wetland is an appropriate treatment for reducing organic matter in the wastewater because it contains both suspended and attached bacterial cells which is the main factor to improve water quality in the system. The criteria of Run 4 is not appropriate to use as the design for CW because it needs a lot of energy to operate the system and it should be recognized that this unit is not suitable for adapting to treat agricultural wastewater which has higher amount of ammonia concentration.

4.5.4 Emergy evaluations of four different treatment systems in Run 2

The analysis from table 4.6 implies that all units have the same total emergy cost for removal wastewater (3.91×10^{12}) and CW systems used lower emergy to improve the nutrients and organic matter treatment efficiencies than that of WSP.

Table 4.5 Comparison for the waste removal efficiencies.

Item	Run 1	Run 2	Run 3	Run 4
Total emergy cost for removal wastewater (sej/d)	2.44×10^{12}	3.91×10^{12}	7.57×10^{12}	1.54×10^{13}
NH_3 removal (g/d)	29.4	34.8	33.0	19.8
PO_4^{3-} removal (g/d)	8.77	9.77	8.00	12.1
BOD removal (g/d)	14.0	17.8	32.8	38.8
EWRP of NH_3 (sej/g)	8.30×10^{10}	1.12×10^{11}	2.29×10^{11}	7.78×10^{11}
EWRP of PO_4^{3-} (sej/g)	2.78×10^{11}	4.00×10^{11}	9.46×10^{11}	1.27×10^{12}
EWRP of BOD (sej/g)	1.75×10^{11}	2.19×10^{11}	2.31×10^{11}	3.97×10^{11}

Table 4.6 Comparison for the waste removal efficiencies among four different treatment systems of Run 2.

Item	CW with fish	CW without fish	WSP with fish	WSP without fish
Total emergy cost for removal wastewater (sej/d)	3.91×10^{12}	3.91×10^{12}	3.91×10^{12}	3.91×10^{12}
NH_3 removal (g/d)	34.8	36.8	30.7	27.6
PO_4^{3-} removal (g/d)	9.77	9.20	6.00	5.78
BOD removal (g/d)	17.84	18.5	6.52	6.86
EWRP of NH_3 (sej/g)	1.12×10^{11}	1.06×10^{11}	1.27×10^{11}	1.42×10^{11}
EWRP of PO_4^{3-} (sej/g)	4.00×10^{11}	4.25×10^{11}	6.52×10^{11}	6.76×10^{11}
EWRP of BOD (sej/g)	2.19×10^{11}	2.11×10^{11}	6.00×10^{11}	5.70×10^{11}

Emergy provided to remove nutrients and organic matter of CW with and without fish were nearby in all parameters. To reduce phosphorus, it used highest emergy more than other parameters for CW both with fish and without fish units. But for WSP both fish and without fish units, high emergy consumption initiated with phosphorus and BOD removal processes. The reason might be linked with high TSS from algal cells present in the systems that needed more energy to remove increased concentrations in wastewater. And also phosphorus removal mechanisms of CW are better than that of WSP especially from soil adsorption and phosphorus uptake by aquatic plant so that WSP systems were necessary to use higher energy for phosphorus treatment than CW.

The total emergy inputs which generated from wastewater and sunlight, was calculated as 3.91×10^{12} for all four units. As can be seen in Figure 4.25-4.26, the emergy stored in water and other parameters including used energy, accounted for largest emergy storage (about 94%) to the emergy inputs for CW both with and without fish. In addition, as revealed by Figure 4.27-4.28, algae cells play the role as largest emergy storage, accounted to 81% of total emergy inputs for WSP both with and without fish. The analysis showed that emergy consumption of CW systems was due to wastewater which is the main target of wastewater treatment plant that we have to invest for this objective. In contrast, the main emergy utilization of WSP systems came from algal cells which have to remove from the systems. This problem brings about the additional operation and maintenance costs that should be taken into account.

In comparison between the units with and without fish, firstly, in the energy transfer point of view, emergy outflow from the units with and without fish

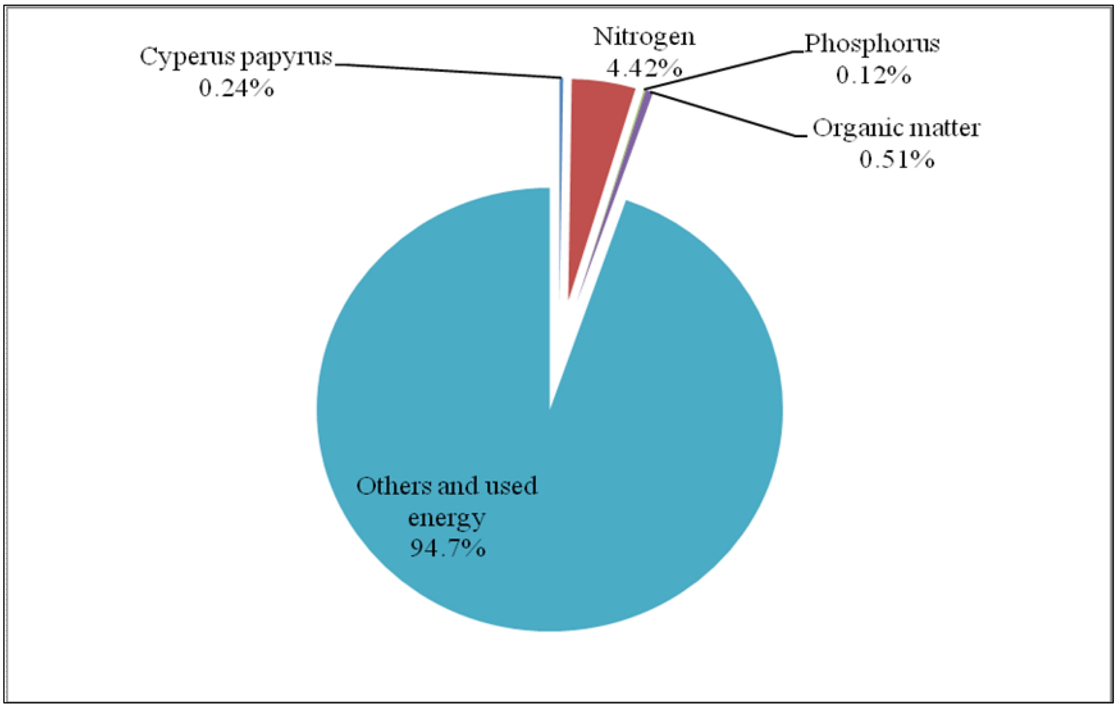


Figure 4.25 Fraction of interest storages in the system boundary of CW without fish.

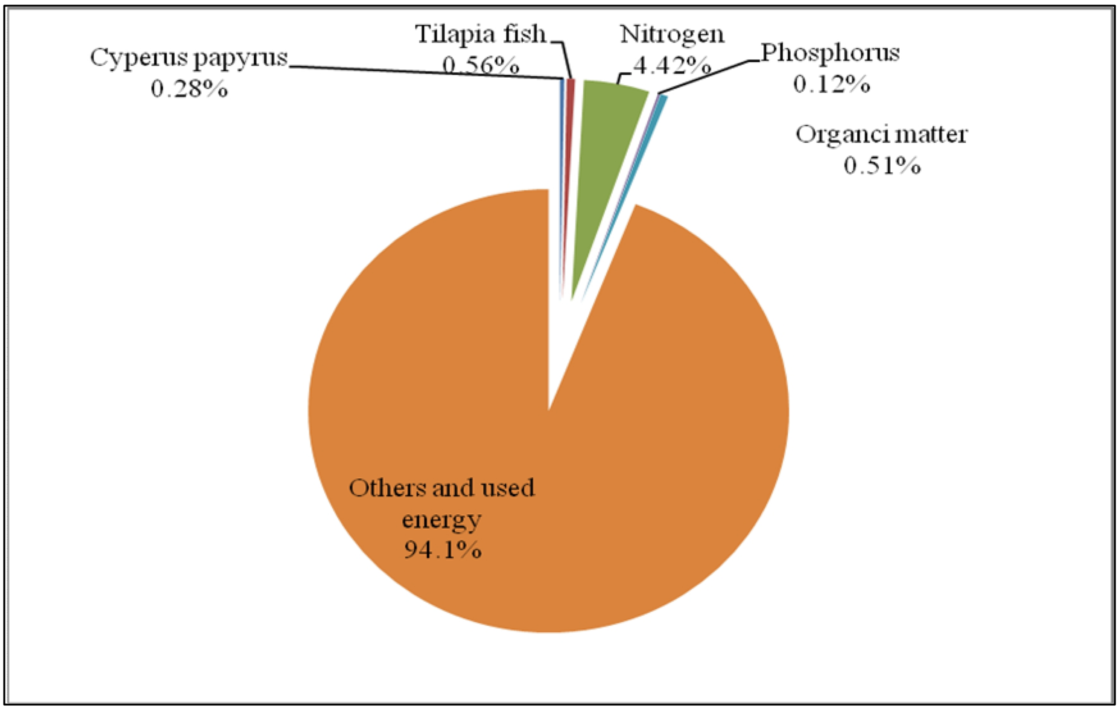


Figure 4.26 Fraction of interest storages in the system boundary of CW with fish.

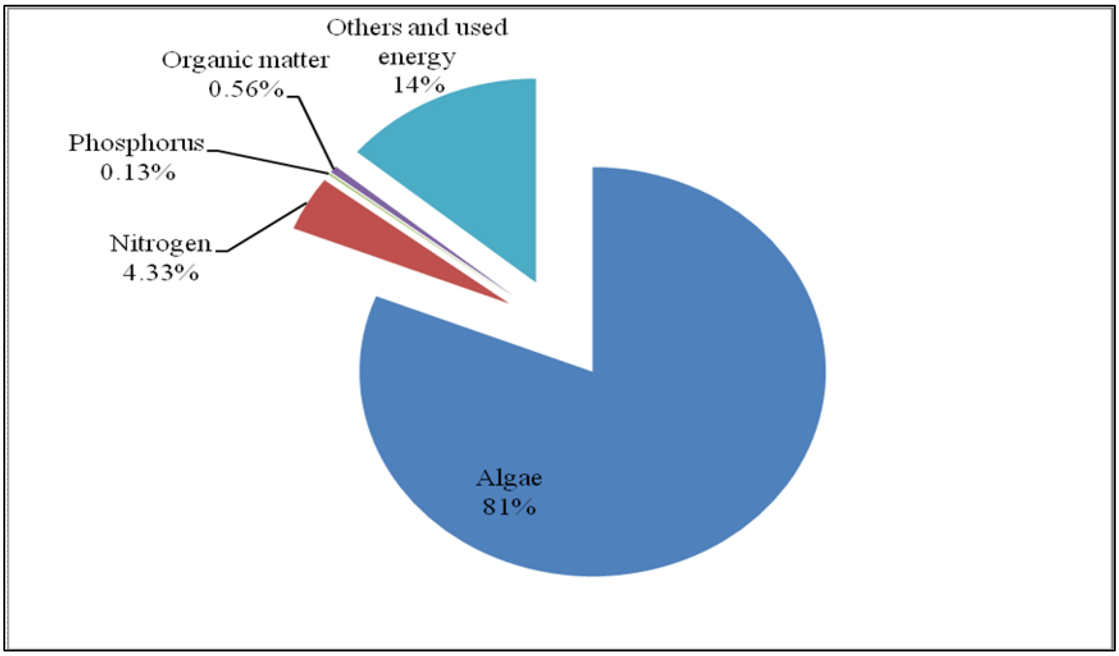


Figure 4.27 Fraction of interest storages in the system boundary of WSP without fish.

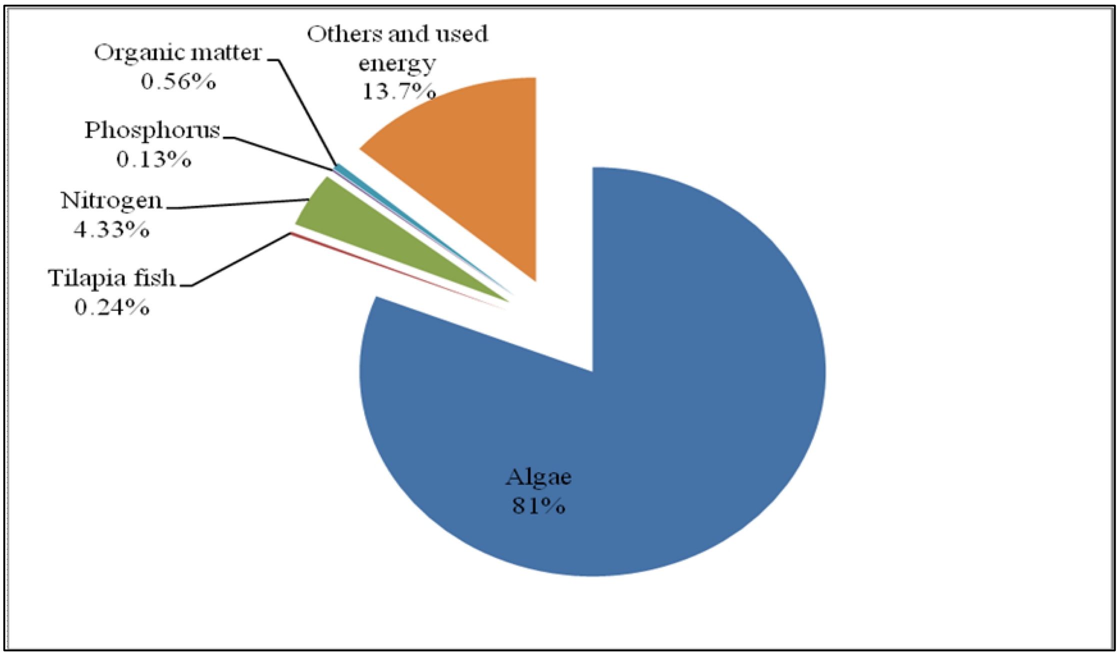


Figure 4.28 Fraction of interest storages in the system boundary of WSP with fish.

were similar in both systems. However, the energy released from units without fish, was useless in the commercial sense, the opportunity for exploitation of the value-added material was lost. In the other hand, the energy within the units with fish could be converted to transform the beneficial product as fish biomass which accounted as a fraction in the system boundary. In addition, fish would consume organic matter present in wastewater input which was considered to be the main driving emergy input in this simulation model. Then, fish helps to remove organic matter in wastewater or can transfer some parts of energy into high trophic level. For this reason, this is the other advantage of fish in the biological wastewater systems. Lastly, if we focus on the technical treatment point of view, some fish cannot tolerate in waste treatment ecosystem or in high-strength wastewater. Thus, the benefit from fish biomass in waste treatment purpose should be minimized and other advantageous target should be taken into account by using the same concept as emergy model.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Four different pilot-scale natural treatment systems were operated to determine the performances of removing organic and nutrients resulting in 10, 16, 31, 63 kg BOD/ha-d. The biomass and productivity of papyrus and fish production were investigated in free water surface wetland with and without fish. Finally, the simulation models were established to describe the relationship among aquatic macrophyte, fish, and some microorganisms in the free water constructed wetland treating domestic wastewater.

In this experimental study, effluent pH was in the range of 6.8-8.0 and 7.3-10.0 for CW and WSP system, respectively. The wastewater temperature was around 25-31°C. The organic and nutrient removal efficiencies between FWS wetlands with and without fish were almost not significantly different. For CW without fish, the overall removal efficiencies ranged from 18-68%, 43-76%, 18-89%, 8.3-93%, 27-74% for COD, BOD, NH_3-N, o-PO_4^{3-}, and TSS, respectively. In addition, the removal efficiencies of these parameters in CW with fish varied between 21-66%, 42-73%, 20-85%, 8.4-90%, 34-79% for COD, BOD, NH_3-N, o-PO_4^{3-}, and TSS, respectively.

From the two-month period of the experiment, the plant biomass of CW with and without fish were found between 2280-2849 g dry weight/m^2 and 2341-3115 g dry weight/m^2, respectively and the plant productivity ranged from 38.00-47.49 g dry weight/m^2-d and 39.02-51.91 g dry weight/m^2-d for CW with and without fish, respectively. This plant could capture almost 5% of solar radiation and converted into organic biomass. In addition to the plant productivity obtained in this study, the nitrogen uptake of papyrus can be estimated to be in the range of 0.64-1.41% and 0.78-1.73% for CW with and without fish, respectively while this plant can take up phosphorus 4-12% for CW with fish and 5-11% for CW without fish. Tilapia fish were introduced into CW system units, the average weight of fish in CW were among 56-65 g per capita and the survival rates are in the range of 75-100%.

Based on the results of this study, it could be concluded that FWS constructed wetland planted with papyrus had a better performance in pollution control in comparison with WSP system, with the optimum period of plant harvesting at about 40 days. In addition, fish rearing in both systems did not significantly reduce the removal efficiencies of FWS wetland and WSP. In contrast, fish introduced in the system, was a value added of CW and WSP in fish production, waste recycling and energy utilization point of views. The disadvantages of CW are about land use and management costs for plant harvesting. Because at the same OLR as WSP (but different HRT), CW needed more areas and medias such as gravel and soil to conduct the treatment plant than that WSP and there are some costs to pay for plant harvesting for example, man power, transportation costs, etc. However, the benefits of plant biomass in CW are well-known both direct and indirect ways such as animal food, handicrafts, decoration and fuel. By the same way, WSP had low potential to treat

BOD and TSS because of the algae in the systems. But if we consider about waste recycling, algae biomass yield has significantly benefit as high protein production. And at the same OLR, WSP could operate more amount of wastewater than that of the CW. So that for selecting the type of wastewater treatment system, the main target should be taken into account.

The results from this study were used to conduct the thermodynamic model and emergy evaluation to emphasize the relationship among aquatic plant, fish and wastewater in CW treatment system. Consequently, emergy evaluation table can be used to compare the performance efficiencies among the different units including plant production efficiency, fish production efficiency and waste removal efficiency. Thermodynamic model is an interesting method to emphasize the relationship among aquatic plant, fish and wastewater in CW treatment system. Six energy equations were developed to predict the plant biomass, fish biomass, water storage, nitrogen storage, phosphorus storage and organic matter storage in 60-day trial period of experiment. The result shows that plant biomass and fish biomass validation in this model, reached to 1.18×10^8 J and 4.42×10^6 J, respectively and these equations can be used as the design approach model with good correlation ($R^2>0.6$) to determine the storages in CW system.

To evaluate performance and embodied energy of the system and also to compare the efficiencies among the different units, emergy analysis table method were used because this method measured product in the same unit as solar emergy which represented the good comparative values. The plant production efficiency was highest in Run 1 about 6.55% conversion which was approximately with the energy capturing efficiency in Chapter 4. Furthermore, fish production efficiency was highest in Run 2 with abundant energy transfer (70%). These production efficiencies are useful for selecting appropriate plant in CW system. According to the main purpose of CW treatment, the emergy waste removal efficiency was established to investigate treatment performance. Run 4 accounted highest emergy used in all parameters because there were high concentrations of nutrients and organic matter in wastewater but it could remove lowest concentration of those parameters. So that it embodied more energy to produce wastewater than other experimental runs.

5.2 Recommendations

Based on the results of this study, some recommendations for further study are listed as follows:

5.2.1 In this study, low-strength wastewater from SUT campus was used. For further study, real domestic wastewater is recommended to use as feed to the constructed wetland so that effect of moderate strength concentration could be observed on the system performance.

5.2.2 Different kinds of fish species and plants use in the constructed wetland should be further investigated as to seek more value added products obtained from the treatment system.

5.2.3 Similarly, more complex emergy analyses of constructed wetland with a variety of fish and plants should be studied in depth so that comparison of different natural treatment systems can be performed.

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APPENDIX A

EXPERIMENTAL DATA OF WATER QUALITY PARAMETERS

Table A.1 Data of COD of constructed wetlands with and without fish for Run 1.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
18/01/05	164.3	38.10	30.80	76.81	81.25
21/01/05	88.00	41.60	38.40	52.73	56.36
24/01/05	75.40	29.68	23.40	60.64	68.97
30/01/05	76.30	48.00	67.20	37.09	11.93
02/02/05	82.50	21.53	16.82	73.90	79.61
05/02/05	110.4	30.07	36.12	72.76	67.28
08/02/05	113.3	16.13	26.52	85.76	76.59
14/02/05	105.2	16.00	34.80	84.79	66.92
17/02/05	184.0	16.00	24.00	91.30	86.96
20/02/05	66.90	22.55	26.31	66.29	60.67
26/02/05	45.60	42.68	50.44	6.40	-10.61
01/03/05	46.56	25.20	21.60	45.88	53.61
04/03/05	92.60	26.32	20.68	71.58	77.67
07/03/05	60.16	41.36	30.08	31.25	50.00
10/03/05	60.16	28.80	25.20	52.13	58.11
13/03/05	93.60	37.12	38.72	60.34	58.63
16/03/05	105.6	15.52	28.88	85.30	72.65
Mean	92.39	29.22	31.76	62.06	59.80
%Removal		68.38	65.62		

Table A.2 Data of COD of waste stabilization ponds with and without fish for Run 1.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/07/05	97.76	63.08	66.40	35.47	32.08
09/07/05	76.40	48.68	38.31	36.28	49.86
17/07/05	59.76	29.20	29.43	51.14	50.75
25/07/05	122.4	84.85	95.18	30.68	22.24
02/08/05	60.16	33.83	45.12	43.77	25.00
10/08/05	184.0	109.4	122.3	40.52	33.53
18/08/05	76.40	59.96	66.40	21.52	13.09
Mean	96.70	61.29	66.16	37.05	32.36
%Removal		36.61	31.58		

Table A.3 Data of COD of constructed wetlands with and without fish for Run 2.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/07/05	97.76	68.28	73.68	30.16	24.63
05/07/05	100.8	67.56	67.68	32.98	32.86
09/07/05	76.40	13.28	29.88	82.62	60.89
13/07/05	59.76	13.28	23.24	77.78	61.11
17/07/05	59.76	24.90	26.56	58.33	55.56
21/07/05	97.76	48.14	41.50	50.76	57.55
25/07/05	122.4	18.26	23.24	85.08	81.01
29/07/05	100.8	41.36	30.08	58.97	70.16
02/08/05	60.16	28.80	25.20	52.13	58.11
06/08/05	93.60	28.22	24.90	69.85	73.40
10/08/05	184.0	52.68	46.08	71.37	74.96
14/08/05	60.16	26.02	26.56	56.75	55.85
18/08/05	76.40	29.88	29.88	60.89	60.89
22/08/05	87.20	35.20	38.71	59.63	55.61
Mean	91.21	35.42	36.23	60.52	58.76
%Removal		61.17	60.28		

Table A.4 Data of COD of waste stabilization ponds with and without fish for Run 2.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
18/01/05	164.3	33.70	39.60	79.49	75.90
22/01/05	87.20	50.40	64.80	42.20	25.69
26/01/05	75.20	33.70	48.05	55.19	36.10
30/01/05	76.30	30.80	38.10	59.63	50.07
03/02/05	102.7	66.00	72.00	35.74	29.89
07/02/05	87.20	70.56	39.20	19.08	55.05
15/02/05	97.76	64.00	52.00	34.53	46.81
19/02/05	72.00	48.88	52.64	32.11	26.89
27/02/05	97.96	58.37	65.96	40.29	32.53
03/03/05	108.6	67.68	78.96	37.70	27.32
07/03/05	60.16	60.16	63.92	0.00	-6.25
11/03/05	97.76	52.64	52.68	46.15	46.11
15/03/05	75.20	41.36	48.88	45.00	35.00
Mean	92.48	52.17	55.14	40.55	37.01
%Removal		43.58	40.38		

Table A.5 Data of COD of constructed wetlands with and without fish for Run 3.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
08/11/05	136.0	100.0	120.0	26.47	11.76
12/11/05	64.00	56.00	56.00	12.50	12.50
17/11/05	40.00	56.00	24.00	-40.00	40.00
21/11/05	52.00	24.00	36.00	53.85	30.77
24/11/05	64.00	16.00	20.00	75.00	68.75
27/11/05	32.00	20.00	16.00	37.50	50.00
03/12/05	40.00	28.00	36.00	30.00	10.00
08/12/05	56.00	20.00	24.00	64.29	57.14
13/12/05	64.00	28.00	20.00	56.25	68.75
18/12/05	72.00	42.00	36.00	41.67	50.00
23/12/05	56.00	16.00	24.00	71.43	57.14
28/12/05	88.00	44.00	52.00	50.00	40.91
02/01/06	96.00	56.00	60.00	41.67	37.50
03/01/06	56.00	24.00	28.00	57.14	50.00
Mean	65.43	37.86	39.43	41.27	41.80
%Removal		42.14	39.74		

Table A.6 Data of COD of waste stabilization ponds with and without fish for Run 3.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
08/11/05	136.0	40.00	28.00	70.59	79.41
13/11/05	64.00	44.00	36.00	31.25	43.75
18/11/05	72.00	20.00	52.00	72.22	27.78
23/11/05	56.00	52.00	52.00	7.14	7.14
28/11/05	56.00	44.00	40.00	21.43	28.57
03/12/05	72.00	52.00	64.00	27.78	11.11
08/12/05	64.00	56.00	64.00	12.50	0.00
13/12/05	64.00	52.00	56.00	18.75	12.50
18/12/05	72.00	56.00	60.00	22.22	16.67
23/12/05	56.00	52.00	56.00	7.14	0.00
28/12/05	88.00	60.00	60.00	31.82	31.82
02/01/06	96.00	44.00	40.00	54.17	58.33
04/01/06	56.00	32.00	16.00	42.86	71.43
Mean	73.23	46.46	48.00	32.30	29.89
%Removal		36.55	34.45		

Table A.7 Data of COD of constructed wetlands with and without fish for Run 4.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/02/06	60.00	56.00	52.00	6.67	13.33
06/02/06	88.00	72.00	72.00	18.18	18.18
10/02/06	60.00	52.00	56.00	13.33	6.67
13/02/06	56.00	48.00	52.00	14.29	7.14
17/02/06	32.00	32.00	16.00	0.00	50.00
20/02/06	56.00	40.00	48.00	28.57	14.29
24/02/06	76.00	60.00	52.00	21.05	31.58
27/02/06	48.00	32.00	40.00	33.33	16.67
10/03/06	88.00	68.00	68.00	22.73	22.73
13/02/06	96.00	77.00	88.00	19.79	8.33
17/03/06	60.00	50.00	48.00	16.67	20.00
20/03/06	64.00	56.00	32.00	12.50	50.00
24/03/06	88.00	68.00	68.00	22.73	22.73
27/03/06	96.00	80.00	82.00	16.67	14.58
31/03/06	64.00	60.00	40.00	6.25	37.50
Mean	68.80	56.73	54.27	16.85	22.25
%Removal		17.54	21.12		

Table A.8 Data of COD of waste stabilization ponds with and without fish for Run 4.

Date	COD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/02/06	60.00	52.00	56.00	13.33	6.67
05/02/06	64.00	60.00	56.00	6.25	12.50
09/02/06	76.00	64.00	60.00	15.79	21.05
12/02/06	88.00	76.00	56.00	13.64	36.36
16/02/06	64.00	56.00	56.00	12.50	12.50
19/02/06	88.00	48.00	68.00	45.45	22.73
23/02/06	48.00	36.00	48.00	25.00	0.00
26/02/06	32.00	16.00	32.00	50.00	0.00
02/03/06	72.00	56.00	56.00	22.22	22.22
05/03/06	48.00	48.00	32.00	0.00	33.33
09/03/06	88.00	60.00	72.00	31.82	18.18
12/03/06	96.00	72.00	84.00	25.00	12.50
16/03/06	122.0	80.00	80.00	34.43	34.43
19/03/06	32.00	56.00	52.00	-75.00	-62.50
23/03/06	56.00	40.00	32.00	28.57	42.86
26/03/06	64.00	52.00	56.00	18.75	12.50
30/03/06	64.00	56.00	44.00	12.50	31.25
Mean	68.35	54.59	55.29	16.49	15.09
%Removal		20.14	19.10		

Table A.9 Data of BOD of constructed wetlands with and without fish for Run 1.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
18/01/05	30.60	7.75	8.05	74.67	73.69
30/01/05	18.40	5.00	4.20	72.83	77.17
05/02/05	31.20	8.00	8.80	74.36	71.79
14/02/05	26.40	7.10	6.90	73.11	73.86
20/02/05	14.20	2.85	3.80	79.93	73.24
26/02/05	10.30	1.40	2.25	86.41	78.16
04/03/05	17.10	5.55	6.20	67.54	63.74
10/03/05	16.50	4.45	5.80	73.03	64.85
16/03/05	25.80	3.80	4.65	85.27	81.98
Mean	21.17	5.10	5.63	76.35	73.17
%Removal		75.91	73.41		

Table A.10 Data of BOD of waste stabilization ponds with and without fish for Run 1.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/07/05	26.20	19.50	19.75	25.57	24.62
09/07/05	16.40	17.85	18.55	-8.84	-13.11
17/07/05	12.30	14.70	14.05	-19.51	-14.23
25/07/05	32.50	24.30	24.40	25.23	24.92
02/08/05	14.80	18.10	18.95	-22.30	-28.04
10/08/05	34.80	27.00	26.50	22.41	23.85
18/08/05	17.60	27.00	27.80	-53.41	-57.95
Mean	22.09	21.21	21.43	-4.41	-5.71
%Removal		3.98	2.98		

Table A.11 Data of BOD of constructed wetlands with and without fish for Run 2.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/07/05	26.20	8.85	9.90	66.22	62.21
09/07/05	16.40	5.65	5.80	65.55	64.63
17/07/05	12.30	3.90	5.10	68.29	58.54
25/07/05	32.50	7.45	8.30	77.08	74.46
02/08/05	14.80	2.70	3.30	81.76	77.70
10/08/05	34.80	7.00	6.70	79.89	80.75
18/08/05	17.60	3.3	4.05	81.25	76.99
Mean	22.09	5.55	6.16	74.29	70.75
%Removal		74.87	72.09		

Table A.12 Data of BOD of waste stabilization ponds with and without fish for Run 2.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
18/01/05	30.60	21.75	22.60	28.92	26.14
26/01/05	20.60	18.25	19.00	11.41	7.77
03/02/05	28.40	17.10	16.90	39.79	40.49
15/02/05	26.80	17.45	17.60	34.89	34.33
27/02/05	25.30	16.10	15.55	36.36	38.54
07/03/05	15.60	17.40	17.60	-11.54	-12.82
15/03/05	19.70	16.10	17.00	18.27	13.71
Mean	23.86	17.74	18.04	22.59	21.16
%Removal		25.66	24.40		

Table A.13 Data of BOD of constructed wetlands with and without fish for Run 3.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
08/11/05	25.30	8.20	9.60	67.59	62.06
17/11/05	12.60	5.70	6.30	54.76	50.00
24/11/05	15.70	9.90	7.50	36.94	52.23
03/12/05	7.80	7.55	8.00	3.21	-2.56
08/12/05	20.60	5.90	7.30	71.36	64.56
13/12/05	24.60	9.40	8.55	61.79	65.24
23/12/05	20.30	11.2	12.2	44.83	39.90
28/12/05	29.60	8.30	8.50	71.96	71.28
02/01/06	26.40	8.50	9.20	67.80	66.15
Mean	20.32	8.29	8.57	53.36	51.98
%Removal		59.19	57.82		

Table A.14 Data of BOD of waste stabilization ponds with and without fish for Run 3.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
08/11/05	25.30	13.95	11.85	44.86	53.16
18/11/05	12.80	6.05	6.50	52.73	49.22
25/11/05	22.40	15.05	15.50	32.81	30.80
03/12/05	7.80	5.10	4.65	34.62	40.38
08/12/05	20.60	13.75	13.55	33.25	34.22
13/12/05	24.60	15.95	16.00	35.16	34.96
23/12/05	20.30	14.10	14.95	30.54	26.35
28/12/05	29.60	14.80	15.85	50.00	46.45
02/01/06	26.40	18.30	19.25	30.68	27.08
Mean	21.09	13.01	13.12	38.30	38.07
%Removal		38.33	37.78		

Table A.15 Data of BOD of constructed wetlands with and without fish for Run 4.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/02/06	16.30	10.15	10.00	37.73	38.65
10/02/06	17.20	11.85	12.75	31.10	25.87
17/02/06	11.50	6.55	6.90	43.04	40.00
24/02/06	20.40	13.00	13.20	36.27	35.29
10/03/06	25.60	14.85	14.25	41.99	44.34
17/03/06	15.70	6.90	7.70	56.05	50.96
24/03/06	24.80	12.60	12.90	49.19	47.98
31/03/06	15.30	8.25	7.50	46.08	50.98
Mean	18.35	10.52	10.65	42.68	41.76
%Removal		42.68	41.96		

Table A.16 Data of BOD of waste stabilization ponds with and without fish for Run 4.

Date	BOD (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/02/06	16.30	12.45	12.90	23.62	20.86
09/02/06	22.40	15.95	16.80	28.79	25.00
16/02/06	15.50	12.60	14.40	18.71	7.10
23/02/06	12.60	8.50	7.65	32.54	39.29
02/03/06	18.90	14.40	14.55	23.81	23.02
09/03/06	24.70	14.45	16.55	41.50	33.00
16/03/06	29.50	16.60	15.80	43.73	46.44
23/03/06	9.20	8.30	7.90	9.78	14.13
30/03/06	12.80	9.35	9.30	26.95	27.34
Mean	19.14	12.92	13.27	29.32	28.26
%Removal		32.50	30.69		

Table A.17 Data of Ammonia nitrogen of constructed wetlands with and without fish for Run 1.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
18/01/05	28.00	4.02	4.20	85.66	85.00
21/01/05	19.10	2.80	2.71	85.34	85.84
24/01/05	16.80	3.64	3.64	78.33	78.33
30/01/05	20.20	1.26	1.68	93.76	91.68
02/02/05	15.60	3.36	3.08	78.46	80.26
05/02/05	16.50	1.78	0.75	89.24	95.45
08/02/05	17.80	4.48	2.66	74.83	85.06
14/02/05	22.50	7.56	4.90	66.40	78.22
17/02/05	21.60	9.52	4.62	55.93	78.61
20/02/05	26.60	2.38	1.54	91.05	94.21
26/02/05	20.20	1.40	2.80	93.07	86.14
01/03/05	19.60	2.52	6.16	87.14	68.57
07/03/05	28.00	2.24	3.92	92.00	86.00
10/03/05	28.00	3.64	1.82	87.00	93.50
13/03/05	24.90	4.48	3.36	82.01	86.51
16/03/05	18.20	3.78	2.24	79.23	87.69
Mean	21.48	3.68	3.13	82.47	85.07
%Removal		82.87	85.43		

Table A.18 Data of Ammonia nitrogen of waste stabilization ponds with and without fish for Run 1.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/07/05	21.76	4.62	6.02	78.77	72.33
09/07/05	7.28	1.26	2.24	82.69	69.23
17/07/05	24.08	7.00	2.66	70.93	88.95
25/07/05	24.92	14.10	3.64	43.44	85.39
02/08/05	19.04	8.40	6.72	55.88	64.71
10/08/05	15.18	3.92	3.92	74.18	74.18
18/08/05	20.72	5.88	6.72	71.62	67.57
Mean	19.00	6.45	4.56	68.22	74.62
%Removal		66.03	76.00		

Table A.19 Data of Ammonia nitrogen of constructed wetlands with and without fish for Run 2.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/07/05	21.76	2.03	3.64	90.67	83.27
05/07/05	17.36	1.12	2.80	93.55	83.87
09/07/05	7.28	2.66	1.90	63.46	73.90
13/07/05	15.18	0.98	3.92	93.54	74.18
17/07/05	24.08	1.96	2.80	91.86	88.37
21/07/05	17.36	1.68	3.78	90.32	78.23
25/07/05	15.48	2.94	4.20	81.01	72.87
29/07/05	24.08	1.54	3.36	93.60	86.05
02/08/05	19.04	1.40	1.68	92.65	91.18
06/08/05	20.72	2.24	2.38	89.19	88.51
10/08/05	15.18	3.36	3.36	77.87	77.87
14/08/05	21.76	2.30	3.36	89.43	84.56
18/08/05	20.72	1.68	1.46	91.89	92.95
22/08/05	17.36	1.54	1.46	91.13	91.59
Mean	18.38	1.96	2.86	87.87	83.39
%Removal		89.34	84.42		

Table A.20 Data of Ammonia nitrogen of waste stabilization ponds with and without fish for Run 2.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
18/01/05	28.00	23.34	3.64	16.66	87.00
22/01/05	24.64	14.10	3.64	42.80	85.23
26/01/05	16.50	2.94	4.76	82.18	71.15
03/02/05	21.30	6.86	4.62	67.79	78.31
07/02/05	25.76	3.22	4.76	87.50	81.52
15/02/05	22.40	6.72	4.62	70.00	79.38
19/02/05	20.20	3.50	4.48	82.67	77.82
27/02/05	26.40	5.88	6.72	77.73	74.55
07/03/05	28.00	4.76	7.56	83.00	73.00
11/03/05	20.60	5.04	8.26	75.53	59.90
15/03/05	18.60	3.64	7.56	80.43	59.35
Mean	22.95	7.27	5.51	69.66	75.20
%Removal		68.31	75.98		

Table A.21 Data of Ammonia nitrogen of constructed wetlands with and without fish for Run 3.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
08/11/05	16.52	5.88	6.72	64.41	59.32
12/11/05	20.72	9.08	9.24	56.18	55.41
17/11/05	7.82	3.36	4.20	57.03	46.29
21/11/05	11.76	2.66	3.64	77.38	69.05
24/11/05	18.76	8.40	6.86	55.22	63.43
27/11/05	7.84	4.62	5.32	41.07	32.14
03/12/05	8.40	4.06	5.04	51.67	40.00
08/12/05	10.08	5.60	5.88	44.44	41.67
13/12/05	13.44	5.60	5.60	58.33	58.33
18/12/05	11.76	4.20	5.04	64.29	57.14
23/12/05	10.08	2.66	3.32	73.61	67.06
28/12/05	16.52	8.40	4.62	49.15	72.03
02/01/06	14.32	6.16	5.60	56.98	60.89
03/01/06	18.76	9.08	9.24	51.60	50.75
Mean	13.34	5.70	5.74	57.24	55.25
%Removal		57.30	57.00		

Table A.22 Data of Ammonia nitrogen of waste stabilization ponds with and without fish for Run 3.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
08/11/05	16.52	11.76	10.50	28.81	36.44
13/11/05	13.44	8.96	7.84	33.33	41.67
18/11/05	14.32	4.34	2.66	69.69	81.42
23/11/05	14.56	5.88	5.88	59.62	59.62
28/11/05	14.56	5.46	5.32	62.50	63.46
03/12/05	6.16	4.62	5.32	25.00	13.64
08/12/05	10.08	4.76	4.48	52.78	55.56
13/12/05	13.44	4.90	5.60	63.54	58.33
18/12/05	11.76	5.04	5.32	57.14	54.76
23/12/05	10.08	4.76	4.48	52.78	55.56
28/12/05	16.52	7.28	7.56	55.93	54.24
02/01/06	14.32	4.62	5.60	67.74	60.89
04/01/06	18.76	8.68	8.56	53.73	54.37
Mean	13.42	6.24	6.09	52.51	53.07
%Removal		53.55	54.66		

Table A.23 Data of Ammonia nitrogen of constructed wetlands with and without fish for Run 4.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/02/06	9.56	8.11	8.40	15.17	12.13
06/02/06	10.08	9.00	8.34	10.71	17.26
10/02/06	11.76	9.95	9.01	15.39	23.38
13/02/06	11.48	8.12	8.12	29.27	29.27
17/02/06	10.64	8.12	8.32	23.68	21.85
20/02/06	11.48	8.12	8.55	29.27	25.52
24/02/06	8.96	7.70	6.99	14.06	21.99
27/02/06	10.64	8.82	7.98	17.11	25.00
10/03/06	9.52	8.18	8.32	14.13	12.66
13/02/06	10.64	7.28	7.84	31.58	26.32
17/03/06	10.64	8.92	8.56	16.21	19.55
20/03/06	7.82	6.30	6.58	19.44	15.86
24/03/06	11.76	9.84	9.10	16.33	22.62
27/03/06	13.44	11.90	11.90	11.46	11.46
31/03/06	11.48	10.36	10.36	9.76	9.76
Mean	10.66	8.71	8.56	18.24	19.64
%Removal		18.26	19.72		

Table A.24 Data of Ammonia nitrogen of waste stabilization ponds with and without fish for Run 4.

Date	Ammonia-N (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/02/06	9.56	8.14	8.87	14.85	7.22
05/02/06	11.76	9.14	9.82	22.28	16.50
09/02/06	9.52	7.92	8.40	16.81	11.76
12/02/06	10.64	7.56	8.48	28.95	20.30
16/02/06	10.64	8.26	8.20	22.37	22.93
19/02/06	10.64	7.28	7.78	31.58	26.88
23/02/06	10.64	9.10	10.10	14.47	5.08
26/02/06	10.64	6.58	7.84	38.16	26.32
02/03/06	8.96	7.00	7.28	21.88	18.75
05/03/06	9.52	7.98	6.86	16.18	27.94
09/03/06	11.48	9.19	10.08	19.95	12.20
12/03/06	13.44	11.22	11.90	16.52	11.46
16/03/06	8.96	7.92	8.19	11.61	8.59
19/03/06	6.16	5.02	6.12	18.51	0.65
23/03/06	14.32	12.41	13.23	13.34	7.61
26/03/06	11.48	9.27	10.08	19.25	12.20
30/03/06	13.44	11.81	12.22	12.13	9.08
Mean	10.69	8.58	9.14	19.93	14.44
%Removal		19.80	14.49		

Table A.25 Data of ortho-phosphate of constructed wetlands with and without fish for Run 1.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
18/01/05	4.44	0.71	0.11	84.12	97.61
21/01/05	4.69	0.55	0.18	88.22	96.25
24/01/05	6.38	0.40	0.17	93.72	97.34
27/01/05	5.76	0.46	0.30	92.10	94.73
02/02/05	7.48	0.64	0.33	91.44	95.64
05/02/05	6.65	1.00	0.63	84.96	90.50
08/02/05	6.09	1.47	0.63	75.86	89.66
14/02/05	6.62	1.36	1.11	79.53	83.23
17/02/05	6.38	1.49	1.42	76.65	77.74
20/02/05	3.42	1.41	0.93	58.90	72.70
26/02/05	5.00	0.86	0.73	82.87	85.38
01/03/05	4.72	1.04	1.11	77.98	76.59
04/03/05	4.69	0.76	0.89	83.81	81.11
07/03/05	7.51	0.41	0.35	94.58	95.40
10/03/05	5.04	0.19	0.52	96.29	89.73
13/03/05	7.24	0.26	0.45	96.37	93.81
16/03/05	5.62	0.52	0.26	90.74	95.45
Mean	5.75	0.79	0.59	85.19	88.99
%Removal					

Table A.26 Data of ortho-phosphate of waste stabilization ponds with and without fish for Run 1.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/07/05	5.12	2.97	2.90	41.99	43.36
09/07/05	6.27	4.84	2.99	22.89	52.31
17/07/05	3.92	2.61	3.50	33.55	10.71
25/07/05	4.72	2.97	3.03	37.08	35.81
02/08/05	5.46	3.48	3.26	36.36	40.38
10/08/05	5.00	3.14	2.70	37.20	46.10
18/08/05	6.27	3.81	4.34	39.31	30.78
Mean	5.25	3.40	3.24	35.48	37.07
%Removal		35.26	38.22		

Table A.27 Data of ortho-phosphate of constructed wetlands with and without fish for Run 2.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/07/05	5.12	1.01	0.39	80.22	92.44
05/07/05	3.92	0.73	0.77	81.33	80.48
09/07/05	6.27	0.45	0.17	92.78	97.33
13/07/05	3.78	0.38	0.47	89.96	87.57
17/07/05	3.92	0.80	0.78	79.59	80.10
21/07/05	5.12	1.15	0.45	77.64	91.16
25/07/05	4.72	0.09	0.10	98.15	97.90
29/07/05	3.42	0.44	0.31	87.19	91.08
02/08/05	5.46	0.64	0.40	88.29	92.75
06/08/05	4.44	0.42	0.23	90.54	94.86
10/08/05	5.00	0.94	0.23	81.30	95.49
14/08/05	3.78	0.67	0.35	82.41	90.67
18/08/05	6.27	0.41	0.25	93.54	96.01
22/08/05	5.12	0.34	0.28	93.33	94.51
Mean	4.74	0.60	0.37	86.88	91.60
%Removal		87.26	92.22		

Table A.28 Data of ortho-phosphate of waste stabilization ponds with and without fish for Run 2.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
18/01/05	4.44	4.35	3.46	2.14	22.18
22/01/05	5.12	4.20	4.05	19.97	21.00
26/01/05	6.48	3.14	2.70	51.54	58.41
03/02/05	7.09	3.92	3.68	44.78	48.10
07/02/05	7.98	3.86	4.13	51.69	48.25
15/02/05	7.21	3.87	4.16	46.32	42.37
19/02/05	8.43	2.47	3.02	70.76	64.18
27/02/05	4.45	2.55	2.40	42.70	46.18
07/03/05	7.50	2.04	2.02	72.80	73.07
11/03/05	5.88	2.81	1.96	52.21	66.75
15/03/05	6.98	1.91	2.23	72.64	68.05
Mean	6.51	3.19	3.07	47.78	50.78
%Removal		50.95	52.79		

Table A.29 Data of ortho-phosphate of constructed wetlands with and without fish for Run 3.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
08/11/05	2.28	0.16	0.21	92.98	91.01
12/11/05	1.41	0.04	0.34	97.16	75.89
17/11/05	3.23	0.77	1.08	76.32	66.56
21/11/05	2.64	0.94	1.23	64.58	53.60
24/11/05	3.65	1.59	1.25	56.44	65.75
27/11/05	2.64	1.33	1.07	49.81	59.47
03/12/05	3.30	1.60	1.85	51.67	43.94
08/12/05	5.69	1.25	1.55	78.03	72.85
13/12/05	3.56	1.07	1.26	69.94	64.61
18/12/05	3.70	1.39	1.64	62.43	55.81
23/12/05	2.64	0.94	1.03	64.58	60.98
28/12/05	3.29	1.92	1.56	41.79	52.58
02/01/06	1.69	1.12	0.91	34.02	46.15
03/01/06	2.69	1.58	1.56	41.45	42.01
Mean	3.03	1.12	1.18	62.94	60.80
%Removal		63.07	61.05		

Table A.30 Data of ortho-phosphate of waste stabilization ponds with and without fish for Run 3.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
08/11/05	2.28	0.42	0.59	81.58	74.12
13/11/05	3.62	1.18	1.48	67.40	59.12
18/11/05	1.46	0.61	0.43	58.22	70.89
23/11/05	3.08	2.25	2.18	26.95	29.38
28/11/05	3.98	2.19	2.88	45.10	27.76
03/12/05	3.30	2.66	3.32	19.55	-0.61
08/12/05	5.69	3.45	3.06	39.46	46.31
13/12/05	3.56	3.57	3.62	-0.28	-1.69
18/12/05	3.70	3.18	3.20	14.19	13.51
23/12/05	2.64	2.39	2.20	9.66	16.67
28/12/05	3.29	1.76	1.67	46.66	49.39
02/01/06	1.69	1.12	1.22	34.02	28.11
04/01/06	2.69	2.24	2.31	16.91	14.31
Mean	3.15	2.08	2.16	35.34	32.87
%Removal		34.16	31.37		

Table A.31 Data of ortho-phosphate of constructed wetlands with and without fish for Run 4.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/02/06	3.28	1.82	2.16	44.66	34.15
06/02/06	3.05	1.79	2.00	41.48	34.43
10/02/06	3.51	1.67	1.81	52.42	48.43
13/02/06	3.46	1.43	1.41	58.67	59.39
17/02/06	2.75	1.55	1.62	43.64	41.27
20/02/06	3.87	1.54	1.54	60.21	60.21
24/02/06	2.89	1.62	1.44	43.94	50.17
27/02/06	3.29	2.03	1.97	38.30	40.27
10/03/06	2.85	1.72	1.81	39.82	36.49
13/02/06	2.80	1.46	1.40	48.04	50.00
17/03/06	2.28	1.51	1.51	33.77	33.77
20/03/06	2.64	1.45	1.31	45.08	50.57
24/03/06	1.69	1.17	1.32	31.07	22.19
27/03/06	3.08	2.50	2.75	18.99	10.88
31/03/06	4.44	2.65	2.67	40.32	39.86
Mean	3.06	1.73	1.78	42.69	40.81
%Removal		43.59	41.83		

Table A.32 Data of ortho-phosphate of waste stabilization ponds with and without fish for Run 4.

Date	ortho-phosphate (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/02/06	3.28	3.07	3.10	6.55	5.49
05/02/06	3.44	3.17	3.17	7.85	7.85
09/02/06	3.05	2.85	2.70	6.56	11.64
12/02/06	4.44	3.97	3.97	10.70	10.70
16/02/06	1.69	1.41	1.51	16.86	10.95
19/02/06	2.89	3.01	2.70	-3.98	6.75
23/02/06	3.87	3.07	3.06	20.67	21.06
26/02/06	3.31	2.94	3.05	11.33	8.01
02/03/06	2.75	2.65	2.66	3.82	3.45
05/03/06	2.85	2.81	2.88	1.58	-1.05
09/03/06	2.56	2.33	2.37	9.18	7.42
12/03/06	1.89	1.81	1.77	4.23	6.35
16/03/06	3.68	3.45	3.52	6.25	4.35
19/03/06	4.12	3.98	4.09	3.52	0.85
23/03/06	1.69	1.30	1.30	23.37	23.37
26/03/06	3.44	3.21	3.12	6.83	9.30
30/03/06	4.27	3.55	3.93	16.86	7.96
Mean	3.13	2.85	2.87	8.95	8.50
%Removal		8.82	8.20		

Table A.33 Data of TSS of constructed wetlands with and without fish for Run 1.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
18/01/05	8.00	3.50	4.50	56.30	43.80
21/01/05	18.00	4.00	4.00	77.80	77.80
24/01/05	20.00	5.50	3.00	72.50	85.00
30/01/05	14.00	6.50	4.50	53.60	67.90
02/02/05	15.00	3.50	2.00	76.70	86.70
05/02/05	16.00	4.50	3.50	71.90	78.10
08/02/05	26.00	7.00	5.00	73.10	80.80
14/02/05	16.00	4.00	4.00	75.00	75.00
17/02/05	20.00	2.50	2.00	87.50	90.00
20/02/05	18.00	2.50	2.00	86.10	88.90
26/02/05	30.00	4.50	2.50	85.00	91.70
01/03/05	15.00	7.00	7.00	53.30	53.30
04/03/05	8.00	2.00	2.00	75.00	75.00
07/03/05	10.00	5.50	4.00	45.00	60.00
10/03/05	12.00	3.00	4.00	75.00	66.70
13/03/05	9.00	2.00	2.00	77.80	77.80
16/03/05	24.00	5.50	3.50	77.10	85.40
Mean	16.41	4.29	3.50	71.68	75.51
%Removal					

Table A.34 Data of TSS of waste stabilization ponds with and without fish for Run 1.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/07/05	16.00	12.00	8.50	25.00	46.90
09/07/05	4.00	3.50	2.50	12.50	37.50
17/07/05	20.00	25.00	23.00	-25.00	-15.00
25/07/05	24.00	28.00	25.50	-16.70	-6.30
02/08/05	16.00	18.00	18.00	-12.50	-12.50
10/08/05	14.00	21.50	25.00	-53.60	-78.60
18/08/05	20.00	36.00	37.00	-80.00	-85.00
Mean	16.29	20.57	19.93	-21.46	-16.14
%Removal		-26.32	-22.37		

Table A.35 Data of TSS of constructed wetlands with and without fish for Run 2.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/07/05	16.00	6.00	7.00	62.50	56.25
05/07/05	28.00	4.50	2.50	83.90	91.07
09/07/05	4.00	4.50	5.00	-12.50	-25.00
13/07/05	10.00	5.50	5.50	45.00	45.00
17/07/05	20.00	11.00	10.50	45.00	47.50
21/07/05	8.00	7.00	4.50	12.50	43.75
25/07/05	24.00	13.00	7.00	45.80	70.83
29/07/05	12.00	2.00	4.00	83.30	66.67
02/08/05	16.00	5.00	5.00	68.80	68.75
06/08/05	20.00	7.00	4.00	65.00	80.00
10/08/05	14.00	4.00	3.00	71.40	78.57
14/08/05	9.00	5.00	3.50	44.40	61.11
18/08/05	20.00	7.00	6.00	65.00	70.00
22/08/05	9.00	2.50	2.50	72.20	72.22
Mean	15.00	6.00	5.00	53.75	59.05
%Removal		60.00	66.67		

Table A.36 Data of TSS of waste stabilization ponds with and without fish for Run 2.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
18/01/05	8.00	3.5	2.0	56.3	75.0
22/01/05	16.00	16.0	15.0	0.0	6.3
26/01/05	24.00	34.0	31.0	-41.7	-29.2
30/01/05	14.00	11.0	10.0	21.4	28.6
03/02/05	8.00	16.0	12.0	-100.0	-50.0
07/02/05	16.00	18.5	11.5	-15.6	28.1
15/02/05	30.00	37.0	35.0	-23.3	-16.7
19/02/05	6.00	16.0	17.0	-166.7	-183.3
27/02/05	18.00	23.0	23.0	-27.8	-27.8
03/03/05	10.00	22.0	26.0	-120.0	-160.0
07/03/05	26.00	32.0	32.0	-23.1	-23.1
11/03/05	20.00	23.0	26.0	-15.0	-30.0
15/03/05	16.00	16.5	18.0	-3.1	-12.5
Mean	16.31	20.65	19.88	-35.28	-30.35
%Removal		-26.65	-21.93		

Table A.37 Data of TSS of constructed wetlands with and without fish for Run 3.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
08/11/05	10.00	4.00	4.00	60.00	60.00
12/11/05	20.00	7.00	6.50	65.00	67.50
17/11/05	12.00	4.00	4.00	66.67	66.67
21/11/05	8.00	7.50	6.00	6.25	25.00
24/11/05	10.00	6.50	7.00	35.00	30.00
27/11/05	16.00	6.00	5.50	62.50	65.63
03/12/05	2.00	4.00	3.50	-100.00	-75.00
08/12/05	6.00	10.00	10.00	-66.67	-66.67
13/12/05	12.00	5.50	6.00	54.17	50.00
18/12/05	20.00	3.50	3.00	82.50	85.00
23/12/05	10.00	5.50	4.00	45.00	60.00
28/12/05	12.00	8.00	9.00	33.33	25.00
02/01/06	8.00	3.50	3.50	56.25	56.25
03/01/06	6.00	2.00	2.00	66.67	66.67
Mean	10.86	5.50	5.29	33.33	36.86
%Removal		49.34	51.32		

Table A.38 Data of TSS of waste stabilization ponds with and without fish for Run 3.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
08/11/05	10.00	8.00	6.00	20.00	40.00
13/11/05	22.00	14.50	13.00	34.09	40.91
18/11/05	14.00	11.00	10.00	21.43	28.57
23/11/05	15.00	13.50	13.00	10.00	13.33
28/11/05	8.00	9.00	9.00	-12.50	-12.50
03/12/05	44.00	24.00	43.00	45.45	2.27
08/12/05	6.00	5.00	3.00	16.67	50.00
13/12/05	12.00	13.00	8.00	-8.33	33.33
18/12/05	20.00	15.00	27.00	25.00	-35.00
23/12/05	10.00	21.50	20.50	-115.00	-105.00
28/12/05	12.00	36.00	18.50	-200.00	-54.17
02/01/06	8.00	14.00	9.50	-75.00	-18.75
04/01/06	6.00	21.50	17.00	-258.33	-183.33
Mean	14.38	15.85	15.19	-38.19	-15.41
%Removal		-10.16	-5.61		

Table A.39 Data of TSS of constructed wetlands with and without fish for Run 4.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		CW without fish	CW with fish	CW without fish	CW with fish
01/02/06	20.00	17.00	16.00	15.00	20.00
06/02/06	12.00	10.50	9.00	12.50	25.00
10/02/06	10.00	8.00	6.50	20.00	35.00
13/02/06	8.00	5.00	4.00	37.50	50.00
17/02/06	16.00	4.50	5.50	71.88	65.63
20/02/06	11.00	12.50	8.50	-13.64	22.73
24/02/06	11.00	6.00	6.00	45.45	45.45
27/02/06	16.00	10.00	5.00	37.50	68.75
10/03/06	10.00	3.00	3.50	70.00	65.00
13/02/06	20.00	13.00	14.00	35.00	30.00
17/03/06	18.00	13.00	12.50	27.78	30.56
20/03/06	12.00	9.00	7.50	25.00	37.50
24/03/06	10.00	8.00	8.00	20.00	20.00
27/03/06	8.00	8.50	9.00	-6.25	-12.50
31/03/06	12.00	14.50	14.00	-20.83	-16.67
Mean	12.93	9.50	8.60	25.13	32.43
%Removal		26.55	33.51		

Table A.40 Data of TSS of waste stabilization ponds with and without fish for Run 4.

Date	TSS (mg/L)			%Removal	
	Influent	Effluent			
		WSP without fish	WSP with fish	WSP without fish	WSP with fish
01/02/06	20.00	15.00	13.00	25.00	35.00
05/02/06	12.00	8.00	8.00	33.33	33.33
09/02/06	16.00	12.00	15.00	25.00	6.25
12/02/06	8.00	14.50	16.00	-81.25	-100.00
16/02/06	8.00	14.50	13.00	-81.25	-62.50
19/02/06	11.00	7.50	7.50	31.82	31.82
23/02/06	11.00	5.00	7.00	54.55	36.36
26/02/06	26.00	27.00	27.50	-3.85	-5.77
02/03/06	10.00	26.00	21.00	-160.00	-110.00
05/03/06	18.00	17.00	18.00	5.56	0.00
09/03/06	18.00	23.00	18.50	-27.78	-2.78
12/03/06	20.00	25.00	21.00	-25.00	-5.00
16/03/06	12.00	16.00	14.00	-33.33	-16.67
19/03/06	24.00	20.00	17.00	16.67	29.17
23/03/06	10.00	8.00	9.00	20.00	10.00
26/03/06	12.00	12.00	16.00	0.00	-33.33
30/03/06	16.00	25.00	21.00	-56.25	-31.25
Mean	14.82	16.21	15.44	-15.11	-10.90
%Removal		-9.33	-4.17		

Table A.41 Data of pH and temperature of constructed wetlands with and without fish for Run 1.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		CW without fish	CW with fish		CW without fish	CW with fish
18/01/05	7.20	7.06	7.05	27.2	25.2	25.5
21/01/05	7.15	7.06	7.06	27.6	25.1	25.2
24/01/05	7.25	7.11	7.10	28.3	27.0	27.0
30/01/05	7.56	7.22	7.20	28.0	26.5	26.0
02/02/05	8.12	7.30	7.31	29.3	26.4	26.4
05/02/05	8.09	7.51	7.55	26.4	28.0	28.0
08/02/05	7.32	7.71	7.92	28.0	27.2	27.1
14/02/05	7.65	7.23	7.15	27.1	28.0	28.0
17/02/05	7.35	7.50	7.70	28.0	26.3	26.3
20/02/05	7.90	7.68	7.34	26.3	25.0	25.0
26/02/05	7.98	7.04	7.33	28.0	27.0	27.0
01/03/05	7.96	6.82	7.06	29.0	26.0	26.0
04/03/05	7.68	7.07	7.08	27.0	25.4	25.4
07/03/05	8.00	7.07	7.08	28.8	26.0	26.0
10/03/05	7.65	7.04	7.05	29.0	25.5	25.5
13/03/05	7.05	7.02	7.02	28.0	26.0	26.0
16/03/05	7.31	7.20	7.19	30.0	27.6	27.4

Table A.42 Data of pH and temperature of waste stabilization ponds with and without fish for Run 1.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		WSP without fish	WSP with fish		WSP without fish	WSP with fish
01/07/05	7.21	9.61	9.39	29.0	30.0	30.0
09/07/05	7.86	8.07	9.62	28.5	30.5	30.5
17/07/05	6.95	8.98	8.81	30.0	28.5	28.5
25/07/05	7.31	8.96	8.79	28.0	26.4	26.4
02/08/05	7.45	8.52	8.89	26.4	29.0	29.0
10/08/05	7.13	8.44	8.85	28.5	28.5	28.5
18/08/05	7.46	7.76	7.52	28.0	27.5	28.0

Table A.43 Data of pH and temperature of constructed wetlands with and without fish for Run 2.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		CW without fish	CW with fish		CW without fish	CW with fish
01/07/05	7.21	7.41	7.65	29.0	26.1	26.2
05/07/05	7.38	7.29	7.33	28.3	25.6	25.7
09/07/05	7.86	7.18	7.16	28.5	26.7	26.5
13/07/05	7.37	6.96	7.13	29.5	27.5	27.5
17/07/05	6.95	7.08	7.22	30.0	27.0	27.0
21/07/05	7.78	7.23	7.22	29.5	27.3	27.3
25/07/05	7.46	7.05	7.11	28.2	26.0	26.0
29/07/05	7.34	7.18	7.03	29.0	26.4	26.4
02/08/05	7.45	6.98	7.11	26.4	28.0	28.0
06/08/05	7.28	7.17	7.05	28.0	25.2	25.2
10/08/05	7.13	7.20	7.06	28.5	28.5	28.5
14/08/05	7.31	7.01	6.85	28.0	26.2	26.3
18/08/05	7.46	7.09	7.09	28.5	26.6	26.6
22/08/05	7.06	6.98	6.96	27.5	26.0	26.5

Table A.44 Data of pH and temperature of waste stabilization ponds with and without fish for Run 2.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		WSP without fish	WSP with fish		WSP without fish	WSP with fish
18/01/05	7.20	8.21	8.20	27	28.7	28.7
22/01/05	7.37	7.95	7.85	29	29.8	29.8
26/01/05	7.32	7.95	7.88	30	27.7	27.65
30/01/05	7.56	8.18	8.13	28	30.5	30.5
03/02/05	8.01	8.29	8.50	30.5	29.0	29
07/02/05	7.79	8.51	8.33	29	29.5	29.5
15/02/05	7.00	7.55	7.29	29.5	28.0	28
19/02/05	7.42	8.58	8.63	28	28.0	28
27/02/05	8.00	7.84	7.76	30.6	29.7	29.7
03/03/05	6.15	9.08	9.09	29.7	29.0	29
07/03/05	8.00	8.18	8.20	29	28.4	28.4
11/03/05	7.04	9.01	9.06	30	29.8	29.8
15/03/05	7.31	8.45	8.50	30	29.0	29

Table A.45 Data of pH and temperature of constructed wetlands with and without fish for Run 3.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		CW without fish	CW with fish		CW without fish	CW with fish
08/11/05	7.49	7.29	7.23	27.0	26.8	26.7
12/11/05	7.36	7.30	7.33	27.0	26.5	26.5
17/11/05	7.56	7.16	7.18	29.0	26.0	26.0
21/11/05	7	7.02	7.04	28.0	25.2	25.2
24/11/05	8.01	7.37	7.30	28.5	27.5	27.5
27/11/05	7.12	7.04	7.03	27.5	26.4	26.4
03/12/05	7.06	7.06	7.06	27.3	26.3	26.3
08/12/05	7.08	7.24	7.22	25.5	24.0	24.0
13/12/05	7.14	7.19	7.11	26.0	25.5	25.5
18/12/05	7.25	7.41	7.40	27.5	26.0	26.0
23/12/05	7.39	7.44	7.36	26.0	24.5	24.5
28/12/05	7.31	7.06	7.08	27.5	27.0	27.0
02/01/06	7.26	7.39	7.31	28.0	25.5	25.4
03/01/06	7.08	7.16	7.17	29.0	26.5	26.5

Table A.46 Data of pH and temperature of waste stabilization ponds with and without fish for Run 3.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		WSP without fish	WSP with fish		WSP without fish	WSP with fish
08/11/05	7.71	7.95	7.91	29	27.3	27.3
13/11/05	7.68	8.05	8.33	29	28.7	28.7
18/11/05	7.56	8.20	8.16	27	27.0	27.0
23/11/05	7.23	7.99	8.41	28	26.6	26.6
28/11/05	7.89	8.00	7.99	27	26.5	26.5
03/12/05	7.06	8.41	8.04	27.3	27.0	27.0
08/12/05	7.08	8.16	7.89	28	27.0	27.0
13/12/05	7.14	8.08	8.09	26	26.0	26.0
18/12/05	7.25	7.99	7.91	27.5	27.0	27.0
23/12/05	7.39	7.92	7.81	26	26.0	26.0
28/12/05	8.31	8.98	9.08	27.5	26.5	26.5
02/01/06	7.26	7.98	7.92	28	27.5	27.5
04/01/06	7.08	8.11	8.14	29	28.4	28.4

Table A.47 Data of pH and temperature of constructed wetlands with and without fish for Run 4.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		CW without fish	CW with fish		CW without fish	CW with fish
01/02/06	7.56	7.27	7.32	29	26.0	27.5
06/02/06	7.71	7.49	7.43	29	27.5	28.3
10/02/06	7.21	7.09	7.08	29.5	26.3	27.9
13/02/06	7.06	7.04	7.03	30.5	26.3	28.4
17/02/06	7.16	7.25	7.27	30	27.5	28.8
20/02/06	7.23	7.37	7.30	29.5	26.7	28.1
24/02/06	7.34	7.35	7.36	29	26.0	27.5
27/02/06	7.45	7.52	7.53	30	27.1	28.6
10/03/06	7.23	7.27	7.24	30	27.6	28.8
13/02/06	7.36	7.26	7.21	29	26.5	27.8
17/03/06	7.12	7.09	7.14	28	25.8	26.9
20/03/06	7.1	7.14	7.19	30.5	27.0	28.8
24/03/06	7.89	7.71	7.74	30	27.6	28.8
27/03/06	7.51	7.40	7.41	30.6	27.2	28.9
31/03/06	7.11	7.09	7.11	29.5	27.8	28.7

Table A.48 Data of pH and temperature of waste stabilization ponds with and without fish for Run 4.

Date	pH			Temperature (°C)		
	Influent	Effluent		Influent	Effluent	
		WSP without fish	WSP with fish		WSP without fish	WSP with fish
01/02/06	7.56	7.92	7.93	30	28.4	28.5
05/02/06	7.21	7.73	7.99	29	27.6	27.6
09/02/06	7.23	7.82	7.65	29.5	29.5	29.5
12/02/06	7.45	7.76	7.83	30.2	29.0	29.0
16/02/06	7.36	7.74	7.90	29	28.5	28.5
19/02/06	7.58	7.97	7.88	28.5	28.0	28.0
23/02/06	7.89	8.14	8.18	28	27.5	27.5
26/02/06	7.06	7.37	7.49	30	29.6	29.6
02/03/06	7.15	7.73	7.76	29	28.3	28.3
05/03/06	7.65	7.94	7.99	29	29.0	29.0
09/03/06	7.3	7.82	7.92	29.5	29.0	29.0
12/03/06	7.42	7.76	7.85	29.8	28.7	28.7
16/03/06	7.11	7.89	7.89	31	29.4	29.4
19/03/06	7.23	7.85	7.96	30.6	29.0	29.0
23/03/06	7.16	7.71	7.81	31	29.0	29.0
26/03/06	7.58	7.79	7.86	30.7	29.4	29.4
30/03/06	7.49	7.79	7.86	30	30.0	30.0

APPENDIX B

EXPERIMENTAL DATA OF NUTRIENTS UPTAKE AND PLANT PRODUCTION

Table B.1 The umbel nitrogen uptake of papyrus.

Run	Umbel, N (mg/g)		N (% dry weight)		N rate($g/m^2/d$)	
	CW without fish	CW with fish	CW without fish	CW with fish	CW without fish	CW with fish
1	6.38	2.68	0.64	0.27	0.147	0.067
2	3.75	3.76	0.37	0.38	0.094	0.111
3	3.81	3.18	0.38	0.32	0.101	0.077
4	5.10	4.73	0.51	0.47	0.161	0.142

Table B.2 The culm nitrogen uptake of papyrus.

Run	Culm, N (mg/g)		N (% dry weight)		N rate($g/m^2/d$)	
	CW without fish	CW with fish	CW without fish	CW with fish	CW without fish	CW with fish
1	3.25	2.42	0.32	0.24	0.052	0.040
2	4.99	5.03	0.50	0.50	0.071	0.083
3	4.18	3.44	0.42	0.34	0.066	0.047
4	4.91	4.67	0.49	0.47	0.099	0.081

Table B.3 The umbel phosphorus uptake of papyrus.

Run	Umbel, P (mg/g)		P (% dry weight)		P rate(g/m^2/d)	
	CW without fish	CW with fish	CW without fish	CW with fish	CW without fish	CW with fish
1	9.69	10.21	0.97	1.02	0.223	0.254
2	7.77	8.08	0.78	0.81	0.195	0.239
3	9.22	11.93	0.92	1.19	0.244	0.290
4	9.52	9.65	0.95	0.97	0.301	0.290

Table B.4 The culm phosphorus uptake of papyrus.

Run	Culm, P (mg/g)		P (% dry weight)		P rate(g/m^2/d)	
	CW without fish	CW with fish	CW without fish	CW with fish	CW without fish	CW with fish
1	7.85	7.69	0.78	0.77	0.125	0.127
2	6.81	6.97	0.68	0.70	0.097	0.115
3	6.43	6.54	0.64	0.65	0.102	0.089
4	7.63	7.13	0.76	0.71	0.154	0.124

Table B.5 Calorific value of papyrus in each part.

Unit	Part	Calorific value (MJ/kg)
Natural	Culm	16.24
	Umbel	18.30
	Total	17.48
CW1/1	Culm	15.08
	Umbel	16.92
	Total	16.18
CW1/2	Culm	15.73
	Umble	17.10
	Total	16.55
CW2/1	Culm	16.81
	Umbel	16.71
	Total	16.75
CW2/2	Culm	16.95
	Umbel	16.83
	Total	16.88

APPENDIX C

THERMODYNAMIC CALCULATION DATA

Table C.1 Description of driving energies, storages and flow data used to calibrate CW with fish model.

Item	Description	Variable	Equation	Calibration		
				Value	Unit	k-value
Input						
1	Sunlight	S		7.26×10^{6}	$J/m^2/d$	
Flows						
2	Remainder sun available	J_{R1}		0.2	n/a	
3	Plant consumed by fish	J_1	$k_1\times F\times C$	2.31×10^{5}	J/d	1.62×10^{-10}
4	Water used by plant	J_2	$k_2\times W_S$	9.85×10^{5}	J/d	1.60×10^{-2}
5	Nitrogen uptake by plant	J_3	$k_3\times N$	1.18×10^{3}	J/d	2.34×10^{-4}
6	Phosphorus uptake by plant	J_4	$k_4\times P$	4.07×10^{2}	J/d	1.67×10^{-3}
7	Organic matter consumed by fish	J_5	$k_5\times OM\times F$	0	J/d	0
8	Treated wastewater	J_6	$k_6\times W_S$	8.35×10^{5}	J/d	1.35×10^{-2}
9	Nitrogen outflow	J_7	$k_7\times N$	1.31×10^{4}	J/d	2.60×10^{-3}
10	Phosphorus outflow	J_8	$k_8\times P$	3.19×10^{2}	J/d	1.31×10^{-3}
11	Organic matter outflow	J_9	$k_9\times OM$	7.59×10^{4}	J/d	4.66×10^{-3}
12	Sun received by plant	J_{10}	$k_{10}\times W_S\times N\times P$	3.48×10^{7}	J/d	4.58×10^{-13}
13	Wastewater inflow	W_W		1.03×10^{6}	J/d	
14	Nitrogen inflow	J_N		8.41×10^{4}	J/d	
15	Phosphorus inflow	J_P		4.07×10^{3}	J/d	
16	Organic matter inflow	J_{OM}		2.72×10^{5}	J/d	

Table C.1 Description of driving energies, storages and flow data used to calibrate CW with fish model (continued).

Item	Description	Variable	Equation	Calibration		
				Value	Unit	k-value
Storage 17	Plant biomass	C		1.38×10^{8}	J	
18	Fish biomass	F		1.02×10^{7}	J	
19	Water	W_S		6.17×10^{7}	J	
20	Nitrogen	N		5.04×10^{6}	J	
21	Phosphorus	P		2.44×10^{5}	J	
22	Organic matter	OM		1.63×10^{7}	J	

Notes and calculations to flow values in Table C.1.

1. Sunlight (Masters, 1998)
2. Remainder sun available estimates as 20% of Sunlight
3. Plant consumed by fish

   Assumed as 10% of plant biomass (Ulgiati and Brown, 2009).

   Plant consumed by fish = $(0.138 \text{ kg/d})\times(0.1)\times(16.77\times10^{6}\text{J/kg})$

   $= 2.31\times10^{5}$ J/d

4. Water used by plant

   From photosynthesis reaction 192 g of biomass comsumed 108 g of water.

   Thus the water used by plant = 77.6 g/d = 77.6 mL/d

   $= (77.6 \text{ mL/d})\times(228.59 \text{ kJ/mol})(1 \text{ mol}/18 \text{ mL})$

   $= 9.85\times10^{5}$ J/d

5. Nitrogen uptake by plant

N uptake by plant biomass = 0.581 g/d = (0.581 g)×(2041 J/g) (Odum and Peterson, 1996)

$= 1.18\times10^{3}$ J/d

6. Phosphorus uptake by plant

P uptake by plant biomass = 1.06 g/d = (1.06 g)×(384 J/g)

$= 4.07\times10^{2}$ J/d (Bardi, 2002)

7. Organic matter consumed by fish (Assumed to be equal 0)

8. Treated wastewater Table C.3

9. Nitrogen outflow

Nitrogen remains in treated wastewater = 6.42 g/d = (6.42 g N)×(2041 J/g)

$= 1.31\times10^{4}$ J/d

10. Phosphorus outflow

Phosphorus remains in treated wastewater = 0.83 g/d = (0.83 g P)×(384 J/g)

$= 3.19\times10^{2}$ J/d

11. Organic matter outflow Table C.3

12. Sunlight received by plant Table C.3

13. Wastewater outflow Table C.3

14. Nitrogen inflow

Nitrogen contains in treated wastewater = 41.2 g/d = (41.2 g N)×(2041 J/g)

$= 8.41\times10^{4}$ J/d

15. Phosphorus inflow

Phosphorus contains in treated wastewater = 10.6 g/d = (10.6 g P)(384 J/g)

$= 4.07\times10^{3}$ J/d

16. Organic matter inflow Table C.3

Table C.2 Emergy evaluation of emergy flows of constructed wetland with fish Run 1.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	6.43×10^{5} J	3.80×10^{6}	2.44×10^{12}
Total input			2.44×10^{12}
Yield			
3 Cyperus papyrus	2.08×10^{6} J	4660	9.72×10^{9}
4 Tilapia fish	1.32×10^{5} J	1.27×10^{5}	1.68×10^{10}
Total yield			2.65×10^{10}
Nonrenewable sources within system			
5 Nitrogen	34.4 g	4.19×10^{9}	1.44×10^{11}
6 Phosphorus	9.78 g	4.60×10^{8}	4.50×10^{9}
7 Organic matter	2.09×10^{5} J	7.40×10^{4}	1.55×10^{10}
Total substrate			1.64×10^{11}
8 Total treated wastewater	5.22×10^{5} J	5.77×10^{6}	3.01×10^{12}
9 Nitrogen outflow	5.00 g	4.19×10^{9}	2.10×10^{10}
10 Phosphorus outflow	1.01 g	4.60×10^{8}	4.65×10^{8}
11 Organic matter outflow	5.58×10^{4} J	7.40×10^{4}	4.13×10^{9}

Table C.3 Emergy evaluation of emergy flows of constructed wetland with fish Run 2.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	1.03×10^{6} J	3.80×10^{6}	3.91×10^{12}
Total input			3.91×10^{12}
Yield			
3 Cyperus papyrus	2.31×10^{6} J	4660	1.08×10^{10}
4 Tilapia fish	1.71×10^{5} J	1.27×10^{5}	2.17×10^{10}
Total yield			3.25×10^{10}
Nonrenewable sources within system			
5 Nitrogen	41.2 g	4.19×10^{9}	1.73×10^{11}
6 Phosphorus	10.6 g	4.60×10^{8}	4.88×10^{9}
7 Organic matter	2.72×10^{5} J	7.40×10^{4}	2.01×10^{10}
Total substrate			1.98×10^{11}
8 Total treated wastewater	8.35×10^{5} J	5.77×10^{6}	4.85×10^{12}
9 Nitrogen outflow	6.42 g	4.19×10^{9}	2.69×10^{10}
10 Phosphorus outflow	0.83 g	4.60×10^{8}	3.82×10^{8}
11 Organic matter outflow	7.59×10^{4} J	7.40×10^{4}	5.62×10^{9}

Table C.4 Emergy evaluation of emergy flows of constructed wetland with fish Run 3.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	1.99×10^{6} J	3.80×10^{6}	7.57×10^{12}
Total input			7.57×10^{12}
Yield			
3 Cyperus papyrus	1.91×10^{6} J	4660	8.91×10^{9}
4 Tilapia fish	1.49×10^{5} J	1.27×10^{5}	1.89×10^{10}
Total yield			2.78×10^{10}
Nonrenewable sources within system			
5 Nitrogen	57.9 g	4.19×10^{9}	2.43×10^{11}
6 Phosphorus	13.1 g	4.60×10^{8}	6.02×10^{9}
7 Organic matter	6.24×10^{5} J	7.40×10^{4}	4.62×10^{10}
Total substrate			2.95×10^{11}
8 Total treated wastewater	1.62×10^{6} J	5.77×10^{6}	9.34×10^{12}
9 Nitrogen outflow	24.9 g	4.19×10^{9}	1.04×10^{11}
10 Phosphorus outflow	5.10 g	4.60×10^{8}	2.35×10^{9}
11 Organic matter outflow	2.63×10^{5} J	7.40×10^{4}	1.95×10^{10}

Table C.5 Emergy evaluation of emergy flows of constructed wetland with fish Run 4.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	4.05×10^{6} J	3.80×10^{6}	1.54×10^{13}
Total input			1.54×10^{13}
Yield			
3 Cyperus papyrus	2.39×10^{6} J	4660	1.11×10^{10}
4 Tilapia fish	1.34×10^{5} J	1.27×10^{5}	1.70×10^{10}
Total yield			2.81×10^{10}
Nonrenewable sources within system			
5 Nitrogen	100.7 g	4.19×10^{9}	4.22×10^{11}
6 Phosphorus	28.9 g	4.60×10^{8}	1.33×10^{10}
7 Organic matter	1.02×10^{6} J	7.40×10^{4}	7.54×10^{10}
Total substrate			5.12×10^{11}
8 Total treated wastewater	3.29×10^{6} J	5.77×10^{6}	1.90×10^{13}
9 Nitrogen outflow	80.9 g	4.19×10^{9}	3.39×10^{11}
10 Phosphorus outflow	16.8 g	4.60×10^{8}	7.73×10^{9}
11 Organic matter outflow	5.91×10^{5} J	7.40×10^{4}	4.37×10^{10}

Table C.6 Algorithm and data sources of CW with fish energy calculation.

No.	Item	Calculation	Units	Sources
1	Sunlight Unit area =	3	m^2	
	Global average solar radiation =	7.26×10^6	$J/m^2/d$	(Masters, 1998)
	Albedo =	20	%	(Odum and Peterson, 1996)
	Energy (J) =	(Area)×(Solar radiation)×(1-Albedo) 1.74×10^7	J/d	
	Transformity =	1 (by definition)	sej/J	(Odum and Peterson, 1996)
2	Wastewater Daily wastewater =	0.10 (Run 1) 0.16 (Run 2) 0.31 (Run 3) 0.63 (Run 4)	m^3/d m^3/d m^3/d m^3/d	
	Gibbs free energy =	6.43×10^6	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	6.43×10^5 (Run 1) 1.03×10^6 (Run 2) 1.99×10^6 (Run 3) 4.05×10^6 (Run 4)	J/d J/d J/d J/d	
	Transformity =	3.80×10^6	sej/J	(Geber and Björklund, 2001)
3	Producer Cyperus papyrus			
	Productivity =	0.124 (Run 1) 0.138 (Run 2) 0.114 (Run 3) 0.142 (Run 4)	kg/d kg/d kg/d kg/d	
	Energy content =	16.77×10^6	J/kg	From the experiments
	Energy (J) =	(Total productivity)×(Energy content)		
	=	2.08×10^6 (Run 1) 2.31×10^6 (Run 2) 1.91×10^6 (Run 3) 2.39×10^6 (Run 4)	J/d J/d J/d J/d	
	Transformity =	4660	sej/J	(Ulgiati and Brown, 2009)

Table C.6 Algorithm and data sources of CW with fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
4	Consumer Tilapia fish			
	Productivity =	7.19×10^{-3} (Run 1) 9.28×10^{-3} (Run 2) 8.08×10^{-3} (Run 3) 7.27×10^{-3} (Run 4)	kg/d kg/d kg/d kg/d	
	Energy content =	18.4×10^{6}	J/kg	(Ridha and Cruz, 2001)
	Energy (J) =	(Total productivity)×(Energy content)		
	=	1.32×10^{5} (Run 1) 1.71×10^{5} (Run 2) 1.49×10^{5} (Run 3) 1.34×10^{5} (Run 4)	J/d J/d J/d J/d	
	Transformity =	1.27×10^{5}	sej/J	(Ulgiati and Brown, 2009)
5	Nutrients Nitrogen (NH_3)			
	Nitrogen content =	34.4 (Run 1) 41.2 (Run 2) 57.9 (Run 3) 100.7 (Run 4)	g/d g/d g/d g/d	
	Transformity =	4.19×10^{9}	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
6	Phosphorus			
	Phosphorus content =	9.78 (Run 1) 10.6 (Run 2) 13.1 (Run 3) 28.9 (Run 4)	g/d g/d g/d g/d	
	Transformity =	4.60×10^{8}	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
7	Organic component energy Organic matter			
	Organic matter content =	0.019 (Run 1)	kg/d	

Table C.6 Algorithm and data sources of CW with fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
		0.0247 (Run 2) 0.0567 (Run 3) 0.0925 (Run 4)	kg/d kg/d kg/d	
	Gibbs free energy =	1.1×10^{7}	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	2.09×10^{5} (Run 1) 2.72×10^{5} (Run 2) 6.24×10^{5} (Run 3) 1.02×10^{6} (Run 4)	J/d J/d J/d J/d	
	Transformity =	7.40×10^{4}	sej/J	(Brown and Bardi, 2001)
8	Treated wastewater			
	Daily wastewater =	0.10 (Run 1) 0.16 (Run 2) 0.31 (Run 3) 0.63 (Run 4)	m^3/d m^3/d m^3/d m^3/d	
	Gibbs free energy =	5.22×10^{6}	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	0.52×10^{6} (Run 1) 0.84×10^{6} (Run 2) 1.62×10^{6} (Run 3) 3.29×10^{6} (Run 4)	J/d J/d J/d J/d	
	Transformity =	5.77×10^{6}	sej/J	(Geber and Björklund, 2001)
9	Nutrient outflow Nitrogen (NH3)			
	Nitrogen content =	5.00 (Run 1) 6.42 (Run 2) 24.9 (Run 3) 80.9 (Run 4)	g/d g/d g/d g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
10	Phosphorus outflow			
	Phosphorus content =	1.01 (Run 1)	g/d	

Table C.6 Algorithm and data sources of CW with fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
		0.83 (Run 2) 5.10 (Run 3) 16.8 (Run 4)	g/d g/d g/d	
	Transformity =	4.60×108	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
11	Organic matter outflow			
	Organic matter content =	0.00507 (Run 1) 0.00690 (Run 2) 0.0239 (Run 3) 0.0537 (Run 4)	kg/d kg/d kg/d kg/d	
	Gibbs free energy =	1.1×10^7	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	5.58×10^4 (Run 1) 7.59×10^4 (Run 2) 2.63×10^5 (Run 3) 5.91×10^5 (Run 4)	J/d J/d J/d J/d	
	Transformity =	7.40×10^4	sej/J	(Brown and Bardi, 2001)

Table C.7 Emergy evaluation of emergy flows of constructed wetland without fish Run 2.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	1.03×10^{6} J	3.80×10^{6}	3.91×10^{12}
Total input			3.91×10^{12}
Yield			
3 Cyperus papyrus	1.98×10^{6} J	4660	9.23×10^{9}
Total yield			9.23×10^{9}
Nonrenewable sources within system			
4 Nitrogen	41.2 g	4.19×10^{9}	1.73×10^{11}
5 Phosphorus	10.6 g	4.60×10^{8}	4.88×10^{9}
6 Organic matter	2.72×10^{5} J	7.40×10^{4}	2.01×10^{10}
Total substrate			1.98×10^{11}
7 Total treated wastewater	8.35×10^{5} J	5.77×10^{6}	4.85×10^{12}
8 Nitrogen outflow	4.39 g	4.19×10^{9}	1.84×10^{10}
9 Phosphorus outflow	1.40 g	4.60×10^{8}	6.44×10^{8}
10 Organic matter outflow	6.84×10^{4} J	7.40×10^{4}	5.06×10^{9}

Table C.8 Algorithm and data sources of CW without fish energy calculation.

No.	Item	Calculation	Units	Sources
1	Sunlight Unit area =	3	m^2	
	Global average solar radiation =	7.26×10^6	$J/m^2/d$	(Masters, 1998)
	Albedo =	20	%	(Odum and Peterson, 1996)
	Energy (J) =	(Area)×(Solar radiation)×(1-Albedo)		
	=	1.74×10^7	J/d	
	Transformity =	1 (by definition)	sej/J	(Odum and Peterson, 1996)
2	Wastewater			
	Daily wastewater =	0.16 (Run 2)	m^3/d	
	Gibbs free energy =	6.43×10^6	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	1.03×10^6 (Run 2)	J/d	
	Transformity =	3.80×10^6	sej/J	(Geber and Björklund, 2001)
3	Producer Cyperus papyrus			
	Productivity =	0.118 (Run 2)	kg/d	
	Energy content =	16.77×10^6	J/kg	From the experiments
	Energy (J) =	(Total productivity)×(Energy content)		
	=	1.98×10^6 (Run 2)	J/d	
	Transformity =	4660	sej/J	(Ulgiati and Brown, 2009)
4	Nutrients Nitrogen (NH3)			
	Nitrogen content =	41.2 (Run 2)	g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
5	Phosphorus			
	Phosphorus content =	10.6 (Run 2)	g/d	

Table C.8 Algorithm and data sources of CW without fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
	Transformity =	4.60×10^{8}	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
6	Organic component energy Organic matter			
	Organic matter content =	0.0247 (Run 2)	kg/d	
	Gibbs free energy =	1.1×10^{7}	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	2.72×10^{5} (Run 2)	J/d	
	Transformity =	7.40×10^{4}	sej/J	(Brown and Bardi, 2001)
7	Treated wastewater Daily wastewater =	0.16 (Run 2)	m^3/d	
	Gibbs free energy =	5.22×10^{6}	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	0.84×10^{6} (Run 2)	J/d	
	Transformity =	5.77×10^{6}	sej/J	(Geber and Björklund, 2001)
8	Nutrient outflow Nitrogen (NH3)			
	Nitrogen content =	4.39 (Run 2)	g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
9	Phosphorus outflow Phosphorus content =	1.40 (Run 2)	g/d	
	Transformity =	4.60×108	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)

Table C.8 Algorithm and data sources of CW without fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
10	Organic matter outflow			
	Organic matter content =	0.00622 (Run 2)	kg/d	
	Gibbs free energy =	1.1×10^{7}	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	6.84×10^{4} (Run 2)	J/d	
	Transformity =	7.40×10^{4}	sej/J	(Brown and Bardi, 2001)

Table C.9 Emergy evaluation of emergy flows of waste stabilization pond with fish Run 2.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	1.03×10^{6} J	3.80×10^{6}	3.91×10^{12}
Total input			3.91×10^{12}
Yield			
3 Algae	0.48 g	6.6×10^{12}	3.17×10^{12}
4 Tilapia fish	7.49×10^{4} J	1.27×10^{5}	9.51×10^{9}
Total yield			3.18×10^{12}
Nonrenewable sources within system			
5 Nitrogen	40.4 g	4.19×10^{9}	1.69×10^{11}
6 Phosphorus	11.4 g	4.60×10^{8}	5.24×10^{9}
7 Organic matter	2.94×10^{5} J	7.40×10^{4}	2.81×10^{10}
Total substrate			1.96×10^{11}
8 Total treated wastewater	8.35×10^{5} J	5.77×10^{6}	4.85×10^{12}
9 Nitrogen outflow	9.70 g	4.19×10^{9}	4.06×10^{10}
10 Phosphorus outflow	5.40 g	4.60×10^{8}	2.48×10^{9}
11 Organic matter outflow	2.22×10^{5} J	7.40×10^{4}	1.64×10^{10}

Table C.10 Algorithm and data sources of WSP with fish energy calculation.

No.	Item	Calculation	Units	Sources
1	Sunlight Unit area =	3	m^2	
	Global average solar radiation =	7.26×10^6	$J/m^2/d$	(Masters, 1998)
	Albedo =	20	%	(Odum and Peterson, 1996)
	Energy (J) =	(Area)×(Solar radiation)×(1-Albedo)		
	=	1.74×10^7	J/d	
	Transformity =	1 (by definition)	sej/J	(Odum and Peterson, 1996)
2	Wastewater Daily wastewater =	0.16 (Run 2)	m^3/d	
	Gibbs free energy =	6.43×10^6	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	1.03×10^6 (Run 2)	J/d	
	Transformity =	3.80×10^6	sej/J	(Geber and Björklund, 2001)
3	Producer Algae			
	Productivity =	0.48 (Run 2)	g/d	
	Transformity =	6.6×10^{12}	sej/g	(Brown and Bardi, 2001)
4	Consumer Tilapia fish			
	Productivity =	4.07×10^{-3} (Run 2)	kg/d	
	Energy content =	18.4×10^6	J/kg	(Ridha and Cruz, 2001)
	Energy (J) =	(Total productivity)×(Energy content)		
	=	7.49×10^4 (Run 2)	J/d	
	Transformity =	1.27×10^5	sej/J	(Ulgiati and Brown, 2009)
5	Nutrients Nitrogen (NH3)			
	Nitrogen content =	40.4 (Run 2)	g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)

Table C.10 Algorithm and data sources of WSP with fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
6	Phosphorus Phosphorus content =	11.4 (Run 2)	g/d	
	Transformity =	4.60×10^{8}	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
7	Organic component energy Organic matter			
	Organic matter content =	0.0267 (Run 2)	kg/d	
	Gibbs free energy =	1.1×10^{7}	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	2.94×10^{5} (Run 2)	J/d	
	Transformity =	7.40×10^{4}	sej/J	(Brown and Bardi, 2001)
8	Treated wastewater Daily wastewater =	0.16 (Run 2)	m^3/d	
	Gibbs free energy =	5.22×10^{6}	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	0.84×10^{6} (Run 2)	J/d	
	Transformity =	5.77×10^{6}	sej/J	(Geber and Björklund, 2001)
9	Nutrient outflow Nitrogen (NH3)			
	Nitrogen content =	9.70 (Run 2)	g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
10	Phosphorus outflow Phosphorus content =	5.40 (Run 2)	g/d	
	Transformity =	4.60×108	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)

Table C.10 Algorithm and data sources of WSP with fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
11	Organic matter outflow			
	Organic matter content =	0.02020 (Run 2)	kg/d	
	Gibbs free energy =	1.1×10^7	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	2.22×10^5 (Run 2)	J/d	
	Transformity =	7.40×10^4	sej/J	(Brown and Bardi, 2001)

Table C.11 Emergy evaluation of emergy flows of waste stabilization pond without fish Run 2.

Item	Raw units (/d)	Transformity (sej/unit)	Solar emergy (sej/d)
Renewable resource			
1 Sunlight	1.74×10^{7} J	1	1.74×10^{7}
Total wastewater			
2 Wastewater	1.03×10^{6} J	3.80×10^{6}	3.91×10^{12}
Total input			3.91×10^{12}
Yield			
3 Algae	0.48 g	6.6×10^{12}	3.17×10^{12}
Total yield			3.17×10^{12}
Nonrenewable sources within system			
4 Nitrogen	40.4 g	4.19×10^{9}	1.69×10^{11}
5 Phosphorus	11.4 g	4.60×10^{8}	5.24×10^{9}
6 Organic matter	2.94×10^{5} J	7.40×10^{4}	2.81×10^{10}
Total substrate			1.96×10^{11}
7 Total treated wastewater	8.35×10^{5} J	5.77×10^{6}	4.85×10^{12}
8 Nitrogen outflow	12.8 g	4.19×10^{9}	5.36×10^{10}
9 Phosphorus outflow	5.62 g	4.60×10^{8}	2.59×10^{9}
10 Organic matter outflow	2.18×10^{5} J	7.40×10^{4}	1.61×10^{10}

Table C.12 Algorithm and data sources of WSP without fish energy calculation.

No.	Item	Calculation	Units	Sources
1	Sunlight Unit area =	3	m^2	
	Global average solar radiation =	7.26×10^6	$J/m^2/d$	(Masters, 1998)
	Albedo =	20	%	(Odum and Peterson, 1996)
	Energy (J) =	(Area)×(Solar radiation)×(1-Albedo)		
	=	1.74×10^7	J/d	
	Transformity =	1 (by definition)	sej/J	(Odum and Peterson, 1996)
2	Wastewater Daily wastewater =	0.16 (Run 2)	m^3/d	
	Gibbs free energy =	6.43×10^6	J/m^3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	1.03×10^6 (Run 2)	J/d	
	Transformity =	3.80×10^6	sej/J	(Geber and Björklund, 2001)
3	Producer Algae			
	Productivity =	0.48 (Run 2)	g/d	
	Transformity =	6.6×10^{12}	sej/g	(Brown and Bardi, 2001)
4	Nutrients Nitrogen (NH3)			
	Nitrogen content =	40.4 (Run 2)	g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
5	Phosphorus Phosphorus content =	11.4 (Run 2)	g/d	
	Transformity =	4.60×108	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
6	Organic component energy Organic matter			
	Organic matter content =	0.0267 (Run 2)	kg/d	

Table C.12 Algorithm and data sources of WSP without fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
	Gibbs free energy =	1.1×107	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	2.94×105 (Run 2)	J/d	
	Transformity =	7.40×104	sej/J	(Brown and Bardi, 2001)
7	Treated wastewater Daily wastewater =	0.16 (Run 2)	m3/d	
	Gibbs free energy =	5.22×106	J/m3	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Daily wastewater)×(Gibbs free energy)		
	=	0.84×106 (Run 2)	J/d	
	Transformity =	5.77×106	sej/J	(Geber and Björklund, 2001)
8	Nutrient outflow Nitrogen (NH3)			
	Nitrogen content =	12.8 (Run 2)	g/d	
	Transformity =	4.19×109	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
9	Phosphorus outflow Phosphorus content =	5.62 (Run 2)	g/d	
	Transformity =	4.60×108	sej/g	(Bastianoni, Marchettini, Niccolucci, and Pulselli, 2005)
10	Organic matter outflow Organic matter content =	0.01986 (Run 2)	kg/d	
	Gibbs free energy =	1.1×107	J/kg	(Wu, Franz, and Chen, 2001)
	Energy (J) =	(Organic matter content)×(Gibbs free energy)		
	=	2.18×105 (Run 2)	J/d	

Table C.12 Algorithm and data sources of WSP without fish energy calculation (continued).

No.	Item	Calculation	Units	Sources
	Transformity =	7.40×104	sej/J	(Brown and Bardi, 2001)

BIOGRAPHY

Miss Thaneeya Perbangkhem was born on October 8, 1978 in Yala, Thailand. After completing her secondary education from the Prince of Songkla University Demonstration School, Pattani province in 1996, she continued her college study in the school of Environmental Engineering, Suranaree University of Technology (SUT), Nakhon Ratchasima province. She graduated in 2001 with a bachelor of engineering degree with honor. Then she earned the Royal Golden Jubilee Ph.D. Scholarship (RGJ–Ph.D.) from the Thailand Research Fund (TRF) to pursue the doctoral program in the same school at SUT.