Supplementary data

Water Quality Degradation and Management Strategies for Swine and Rice Farming Wastewater in the Tha Chin River Basin

Table S1. Swine wastewater treatment options

Treatment type	BOD removal efficiency (%) by farm size	Advantages	Disadvantages
Anaerobic lagoon	50-85	Do not need aerators	Lower nutrient and BOD removal efficiency than other lagoons; affected by temperature variation fecal coliforms remain; large area needed; odor
Aerobic lagoon	60-80	Higher nutrient and BOD removal efficiency than anaerobic lagoons	Need aerators; large area needed; odor
Facultative lagoon	80-95	Both anaerobic and aerobic zones	Large area needed; odor
Multiple lagoon system	Large: 90.51 Medium: 78.52 Small: 77.78	Treatment advantages of all pond types	Largest area needed; odor
Anaerobic filter tank	Medium: 78.52	For small and medium farms; durable; quick construction	Low capacity; maintenance and monitoring required
Anaerobic digester (see S2)	69-93	Electricity/heat energy and fertilizer coproducts	Effective at high temperature; energy costs associate with temperature

(Kashyap, 2017, who cites Seanghaisuck, 2015; Sobsey, 2006)

Table S2. Details on anaerobic digester systems for biogas recovery

System	BOD removal efficiency (%) by farm size	Advantages	Disadvantages
Fixed dome	Medium: 75.86 Small: 85.06	Already promoted by governmental agencies; reduces odor; minimal maintenance; long life span; minimal space; low temperature variation	Pond required for wastewater treatment; difficult to construct; technical skills required
Plastic bag	76-92	Developed and implemented by Thai government; good for small farms; easy implementation and maintenance; includes post treatment ponds and drying beds	Pond required for wastewater treatment; short life span; require large surface
Covered lagoon	Large: 85.91 Medium: 69.83 Small: 85.18	Less concrete; quick construction; feasible in warmer climates	Pond required for wastewater treatment; large area required; high retention time
Channel digester with UASB	Large: 92.90 Medium: 85.47	For medium and large sized farms; developed and implemented by Thai government	Pond required for wastewater treatment

(Chaipipat, 1999; EPA, 2011; Kashyap, 2017; Nokyoo, 2016; Shane, 2017)

Table S3. Potential expenses saved per subdistrict based on a switch to a biogas network pipeline

Province	Subdistrict	Subdistrict pasture Area (km^2)	Number of households	LPG usage (kg/day)	Biogas equivalent (m^3/day)	Expenses of LPG (1000$ /year)	Expenses of biogas (1000$ /year)	Expenses potentially saved (1000$ /year)
Suphanburi	Ton Tan	4.2	1049	240	530	70	13	53
	Bang Ta Then	1.1	5321	1220	2660	330	65	270
	Bang Ta Khian	1.3	1609	370	810	100	19	82
Nakhon Pathom	Sampathuan	2.0	1262	290	630	80	15	64
	Bang Lan	1.7	2212	510	1110	140	27	112
	Bang Luang	1.3	2256	520	1130	140	27	115
	Hin Mun	1.2	1773	410	890	110	21	90

(Wonsapai, 2016)

S4: Information about biogas in Thailand

With biogas generators, swine farms can generate electrical and heat energy for use on-farm or to sell back to the grid. Some biogas systems also produce a fertilizer by-product that can be sold or used for crops. (Shane, 2017). For these reasons, biogas digesters for swine farming have already been recognized as promising technology and have been implemented in Thailand, as biogas has been one of the most successful renewable energy projects in Thailand (Wongsapai et al., 2008). The Department of Alternative Energy Development and Efficiency (DEDE) has released an Alternative Energy Development Plan for 2015 which includes a goal of 1280 MW of electrical biogas energy production and 1283.44 kilo-tonnes of oil equivalent (ktoe) of heat biogas energy by 2036; in 2016, 434.86 MW and 592 ktoe, respectively, were generated (DEDE, 2016). As the swine farming industry continues to grow in Thailand, further implementation of swine biogas digesters is a feasible way for Thailand to meet this goal.

The Royal Thai Government has subsidized almost 28 million USD for investment in on-farm biogas generators for medium and large swine farms in the years 1995-2009; these subsidies cover 33% of the implementation costs, leaving the farmer to cover the rest of the costs. Due to the high construction, operation and maintenance costs, the small-subsidized portion of coverage by the Thai government has led to shared ownership of these biogas reactors by multiple small operation farmers. These generators have post-water treatment technology that allows the wastewater to follow point-source pollution standards (Wongsapai et al., 2008).

Aside from subsidies and project implementation, the government can also incentivize biogas digesters through restructuring of the energy grid; a sensitivity analysis showed that the best-case situation for swine farmers involved allowing the sale of excess energy back to the EGAT energy grid (Kiratikarnkul, 2010). Currently, a Feed in Tariff (FiT) is in place to subsidize 3.76 Baht/kWh for wastewater projects in a 20-year commitment (Peerapong and Limmeechokchai, 2016). This FiT favors smaller (1 MW) systems and currently only includes projects that have signed Power Purchasing Agreements (PPAs), but not yet sold energy back to the grid (Chrometzka and Ananjavanich, 2015). The Provincial Electricity Authority (PEA) announced intention to buy electricity from junior power producers—which include swine farms—in a PPA; this agreement was criticized for having only tentative commitments to energy purchases and failed to receive international lending (World Bank, 2009).

Table S5. Wetland benefits and flow patterns

Constructed wetland type	Flow direction	Major processes	Flow of wastewater
Subsurface	Horizontal	Anaerobic microbial organic substance removal; sedimentation; denitrification	Influent enters through inlet; forced slowly through substrate
	Vertical	Ammonia volatilization; denitrification-bottom up; sedimentation	Water percolates through substrate; influent collected at bottom of cell and pumped to next treatment; batch fed using timer controlled pump
Free water	Horizontal	Anaerobic microbial organic substance removal; sedimentation; denitrification and nitrification; ammonification/ volatilization; phosphorus removal; metal/pathogen removal	Wastewater discharged into the system, flows over a vegetated surface, then follows the natural flow of the river

(EPA, 1993) (EPA, 2000)

Table S6. Substrate recommendations for constructed wetlands

Substrate	Cost ($/unit)	Unit	Advantages	Disadvantages
Bamboo Splint	0.60	m^2	Inexpensive; does not harm environment; may make up for secondary pollution caused by other substrates; very porous; higher moisture content; high nitrogen (N) removal efficiency	Not effective at phosphorus (P) removal; poor COD removal
Sand	13	m^3	Adding calcite and crushed marble could enhance P-absorption; coarse sand in filter beds provide a surface for microbial growth; supports adsorption and filtration; efficiency in filtration; biofilms on the media reduce harmful pathogens in water by filtration and adsorption	Not effective at P removal; highly variable between types of sand removal
Oil Palm Shell	60	t	Large surface area; low sugar; not liable to insect; strong water resistance; great intensively; high COD/TP removal efficiency; effective for removal of heavy metals; increased shoot regeneration rate, plant height growth, and dry biomass gain opposed to dirt	Palm oil derivation is very destructive to the environment
Gravel	6	m^3	Inexpensive; replacement not necessary; biofilms on the media reduce harmful pathogens in water by filtration and adsorption	Not effective at P removal; not as good at filtration as sand

Table S6. Substrate recommendations for constructed wetlands (cont.)

Substrate	Cost ($/unit)	Unit	Advantages	Disadvantages
Clay Aggregate	22	m^3	Effective at P removal; rapid P initial absorption, but after surface cover increases, P is weakly adsorbed	Becomes P saturated (~5-6 years) then removal efficiency decreases; likely has to be removed and replaced (costly and difficult); forms aluminum phosphate precipitate
Steel Slag	600	t	Effective at P removal; reactive iron/aluminum hydroxide on surface absorb P; nearly 100% P removal efficiency over 80 days; avg E.Coli removal of 87.8% during first 350 days and 78.1% over 100 days	Become P saturated (~5-6 years) then removal decreases; likely has to be removed and replaced (costly and difficult)

(Commenwealth of Australia, 2016; Dordio, 2013; Kivaisi, 2001; Liu et al., 2008; The Ramsar Convention on Wetlands, 2008)

Table S7. Macrophyte recommendations

Macrophyte	Recommended wetland	Advantages	Disadvantages
Phragmites australis	Free surface/ subsurface	Nutrient removal performance stable and efficient; substantial N storage; rapid vegetative propagation; can spread over 0.05 ha/2yr; difficult to eradicate once established; highest aboveground N/P removal/biomass production/water consumption of tested herbaceous perennials	Undesirable conditions for precipitation of Ni; does not remove heavy metals efficiently; can suppress graminoids; suggested functional inequivalence to other marsh species; may result in a net loss of ecosystem function
Typha latifolia (Broadleaf Cattail)	Free surface/ subsurface	Shallow water <15cm; acidic or alkaline conditions; suitable for sandy, loamy, and clay soils; efficient removal of organic matter and ammonia N; high biomass yield; utilization of harvested material as fuel; versatile (wide range of habitats); shade tolerant; germinated faster in high nutrient water, especially P rich	Introduced species; quickly inhabits disturbed areas, reducing diversity and productivity; decrease a fauna due to decreased biodiversity of plant species; rapid water fluctuations may affect species fitness
Typha angustifolia (Narrowleaf Cattail)	Free surface/ subsurface	Native to Thailand; able to tolerate seasonal droughts, salinity fluctuation, and conditions with excessive silt/nutrients; grows rapidly; efficiently removes N/P; efficient at removal of heavy metals such as Fe, Pb, Mg, Cu, Zn, Ni, Cd; can remove dangerous toxins such as arsenic at a rate of 56mg per square meter per day; helps to control algal blooms; outperforms *Juncus effusus* and *Scirpus lacustris* in rate of growth and phytoremediation potential	Can easily dominate in inhospitable niches; decreases biodiversity

Table S7. Macrophyte recommendations (cont.)

Macrophyte	Recommended wetland	Advantages	Disadvantages
Scirpus lacustris (Bulrush)	Subsurface	Persists in various flows; can persist as completely submerged populations in faster flow; N and P removal enhanced in presence, even with low C:N levels; responsible for 30% TB and 20% TP removal in summer-removal; efficiencies of gravel beds with plant are significantly higher than those from other treatments	Introduced species; usually soft silt wetlands; organic C removal not correlated to presence; gravel depth influences growth patterns
Juncus effusus (Common Rush)	Free surface/ subsurface	2-4 ft in height/width w/ Low maintenance; neutralizer; aids in erosions control; able to grow in gravel substrate; 70% efficiency in TSS removal/BOD; ~50-60% removal of TKN/NH3/P; decreases fecal bacteria magnitude - 3	Usually thrives in cool temperate regions
Limnophila villife	Free surface	Native to Thailand; thrives in wet rice fields; perennial herb (extend diversity); submerged stems with exposed 4-5 mm; found in acidic or slightly basic water; efficient photosynthesizer; can grow in low light	Forms mats as leaves break off stems; toxin in stem tissue may prevent fish from eating; optimum temp of 20-26 ºC; max temp of 28 ºC; can outcompete completely submerged plants; clogs irrigation and flood control canals;w eed problem in rice paddies
Peltandra virginica (Green Arrow Arum)	Free surface	Grows in high light and full shade; neutralizer; easily grown in water up to 6 inches; does not colonize aggressively; tolerant to low O_2 levels	Introduced species; invasive species
Frimbristylis sleumeri	Free surface	Native; thrives in swampy grassland; high calcium uptake; high accumulation-organic osmotica; can tolerate higher salinity/nutrient enrichment with efficient uptake rates; found in a variety of diverse locations	Issues with morphological delimitation; considered weeds
Limnophila hayatae	Free surface	Native marsh plant; large surface area for microorganism growth	Can create dense mats
Limnophila verticillata	Free surface	Native marsh plant; source of human nourishment	Threatened; thrives only in full sun
Limnophila siamensis	Free surface	Native; thrives in small ponds/low altitudes	Threatened; not much information
Littorella unifora	Free surface	Native submerged aquatic macrophyte; tolerates low light; creates carpets for fish/benthic wildlife and decreases TSS	Slow growth rate; small root system

Table S7. Macrophyte recommendations (cont.)

Macrophyte	Recommended wetland	Advantages	Disadvantages
Potemogeton crispus (Curled Pondweed)	Free surface	Submerged aquatic macrophyte; high removal efficiency of COD (92.35%), $NH4^+$-N (93.70%), TN (55.62%); viable for removing organics and N	Introduced species; increased NH3 in H2O-no increased response; take caution when treating relatively heavily polluted water
Potamogeton gramineus (Various-Leaved Pondweed)	Free surface	Floating leaved macrophyte High removal efficiency of COD (92.35%), $NH4^+$-N (93.70%), TN (55.62%); viable for removing organics and N in shallow nutrient enriched river water ecosystem	Does not alter production in response to increased NH3 in water; take caution when treating relatively heavily polluted water; introduced species
Hydrocotyle vulgarus (Marsh Pennywort)	Free surface	Introduced species; floating leaved macrophyte; creeper-good for lining river edge; can underplant taller species; high nutrient uptake	Dominates other species-beats out native plant species; manipulates resource availability; highly invasive in china
Nymphea alba (European White Water Lily)	Free surface	Floating leaved macrophyte; strong root system; leaf stalks-little effect on flow; shading effect suppresses growth of troublesome submerged plants; high nitrogen uptake	Can produce a dense cover; introduced species; potential eutrophication; can block growth of other plants (competition); low uptake of zinc and copper
Elchhornia crassipes (Water Hyacinth)	Free surface	Introduced species; floating leaved macrophyte; extensive root system for nutrient uptake; sexual/asexual; reproduction-high rates of reproduction	Creates dense mats; can easily displace other species; mats degrade H2O quality; increases mosquito vectors; eutrophication possible
Lemna minor (Common Duckweed)	Free surface	Native floating leaved macrophyte; used to remove nutrients/toxic metals (phytoremediation); fast growing/hardy; easily removed from water after use	Must be maintained and eventually removed; can cause eutrophication; blocks sunlight from submerged aquatic plants

(Chen, 2009; Coleman, 2001; Finlayson et al., 1998; Havens et al., 2003; ISSG, 2006; Lee and Scholz, 2007; Sharp, 2002; Smithsonian Marine Station, 2007; Soto, 1999; United States National Park Service, 2010; University of Hawaii, Manoa, 1993; Veeravaitaya, 2017; VIMS Publications, n.d; WWF, 2017; Xu et al., 2012; Zhang, n.d)

S8. Wetland costs

Table S8a. Reuse submerged constructed wetland cost

Reuse				
Water volume (L/day)	Size (m^2)	Cost construction ($)	Cost per daily flow ($/L)	Number of wetland cells required
10,000-25,000	133-333	50-75,000	5-3	3
25,000-75,000	333-1000	75-125,000	3-1.65	3
75,000-150,000	1,000-2,000	125-225,000	1.65-<1	3

(EPA, 1993)

Table S8b. Discharge submerged constructed wetland cost

Water volume (L/day)	Size (m^2)	Cost Construction ($)	Cost per daily flow ($/L)	Number of wetland cells required
10,000-25,000	400-1,000	65-100,000	6.50-4	4
25,000-75,000	1,000-3,000	100-250,000	4-3.33	4
75,000-150,000	3,000-6,000	250-450,000	3.33-<3	4

(EPA, 1993)

Table S8c. Free water wetland costs

Item	Cost ($)	
	Native Soil Liner	Plastic Membrane Liner
Site Investigation	3,600	3,600
Site cleaning	6,600	6,600
Earthwork	33,000	33,000
Liner	0	66,000
Soil Planting Media	10,600	10,600
Plants	5,000	5,000
Planting	6,600	6,600
Inlets/Outlets	16,600	16,600
O&M per year	6,000	6,000

(EPA, 2000)

S9: Additional wetland information

Each subsurface wetland cell must have a basin with 20-30 cm of substrate, a water depth of 20-40 cm, and planted macrophytes with roots in soil and stems emerging over the surface of water. In these systems, inorganic and organic material is removed by settling, microbial degradation also removes organic material; nitrogen is effectively removed through denitrification and ammonia volatilization. Phosphorus, however, is not significantly removed because wastewater does not come into contact with soil particles, only substrate particles such as gravel, sand, fly ash, or activated charcoal. The system should be designed with a retention period of 3-3.5 days per cell.

Subsurface wetlands have several advantages over free water systems. Subsurface wetlands have a higher contaminant removal rate and a higher surface area for microorganism production. This allows for increased efficiency due to the substrate composition and extensive root system of macrophytes. Macrophyte composition and type only accounts for 10-12% of nutrient uptake in wetland systems; therefore, while free surface wetlands have a higher density and biodiversity, their efficiency is lower due to silt substrate, which provides little surface area for decomposer. In addition, subsurface wetlands have little risk for vector, public, or animal exposure, as wastewater is not exposed to air. Without direct exposure to the surrounding environment, it is difficult for vectors to use the water as a breeding ground, and the likelihood of ingestion of contaminated wastewater by animals and humans is diminished greatly. The percolation of wastewater through substrates decreases the volume of effluent to the river and reduces the organic matter and nutrients in the wastewater (EPA, 2000).

Vertical flow free surface wetland systems are still recommended instead of or in addition to horizontal; their higher heavy metal, nitrogen, and phosphorus uptake efficiencies allow for vast improvements in overall water quality. Criteria for free water surface wetlands are much looser than those for subsurface wetlands. They must contain aquatic plants that can be either free-floating or rooted in a soil layer on the wetland floor. The water moves horizontally through the plant foliage above a chosen substrate. The surface water is typically more aerobic than the deeper waters, which become more anoxic as microorganism concentration increases in a given area. The free surface wetlands can be further classified into floating macrophyte, submerged, or rooted emergent macrophyte systems, although they can contain a combination of more than one type of macrophyte in a given system. Surface flow wetlands have high organic matter accumulation due to a high primary productivity and decomposition rate through anaerobic benthic conditions. They tend to have a primary productivity rate of over 1000 g carbon/m^2/year (Mitsch and Gosselink, 1993). The main advantage of free surface flow wetlands over subsurface is the high phosphorus uptake efficiency. Absorption through binding to iron and aluminum sites in sediments, such as the clay aggregate typically found in Thailand's soil allows for efficiency for 6-13 months if the uptake is not buried beneath new soil layers by that time (Dordio, 2013). The macrophyte species provide added surface area for bacterial growth and increase substrate porosity so as to allow for increases in oxygen concentration; this increase in oxygen concentration allows for nitrification.

Recommended hydraulic loading and organic loading rates are 2-33 mm/day 135 kg/ha/day (EPA, 1993). Trying to offset costs by discharging higher organic and hydraulic loading rates is likely to cause surface flooding attributed to suspended solids (> 400 kg/ha/day results in clogging of the system). Adding a nitrifying column can increase BOD loading rate availabilities.

It is recommended that subsurface systems have a mixed substrate system of gravel and sand, as gravel is low cost and sand has a high surface area, allowing for increased sorption of organic material, and only implement one species of macrophyte that specializes in heavy metal and organic matter uptake.

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