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Review article

Integrated wetlands for food production

Ray Zhuangrui Chen, Ming-Hung Wong

Consortium on Health, Environment, Education and Research (CHEER), and Department of Science and Environmental Studies, The Hong Kong Institute of Education, Tai Po, Hong Kong, PR China

1. Introduction

In order to increase production and enhance production efficiency in modernized conventional food production systems including aquaculture, high nutrient input, density breeding and assembly line production are usually adopted; with addition of pesticides, disinfectants, antibiotics, vaccines, immune-stimulants, and vitamins. However, efficient management for protecting the adjacent environment is either lacking or insufficient, while these conventional production systems also exert harmful effects to the environment (Bunting, 2013; Wong et al., 2004). Eutrophication is one of the greatest adverse environmental impact of modern aquaculture due to intensification through increasing use of pelleted feeds and expansion of the aquaculture area (Edwards, 2015). Almost two third of the nutrients found in feeds are not consumed by cultured fish during growth and released into the immediate environment, with only one third is assimilated by the fish (Edwards, 1993). The residues originated from uneaten feeds, fecal matters and excreta contributed to most of the nutrients that become pollutants stagnated in the environment. Both organic and inorganic matters discharged from aquaculture activities, especially nutrients such as, nitrogen and phosphorus have been involved in stimulating phytoplankton production, and in some instances the development of algal blooms (Bunting, 2013; Jacobs and Harrison, 2014), including toxic algal blooms which may in turn lead to anoxic zones, fish kills, and loss of biodiversity (Anderson, 1989; Backer and McGillicuddy, 2006; Hallegraeff, 2014, 1993; Imai et al., 2014).

Food production is increasingly being adversely affected by agriculture and aquaculture, and also domestic, industry discharges. Pesticide residues have become nonpoint source pollution in waterways which are threatening the drinking water resources and aquatic ecosystems (Dwiyana and Mendoza, 2006; Krone-Davis et al., 2013; Matamoros et al., 2008; Moore et al., 2009; Vymazal and Brezinová, 2015). Ammonia and nitrite arising from degradation of protein can be of primary toxic to aquatic organisms (Bunting, 2013; Kadlec and Zmrhal, 2010; Mook et al., 2012; Tyson, 2007). Antimicrobial resistance (AMR) bacteria detected in consuming animal food products has become an emerging public health concern, for instance, AMR of bacteria was detected in Oysters and Mussels (Rees et al., 2014), pigs and poultry birds (Amaechi et al., 2015), fishes and prawns and also the ambient soil and water ways (Sengeløw et al., 2003; Silvester et al., 2015; Thiele-Bruhn, 2003; Vivekanandhan et al., 2002; Yohanna et al., 2013).

Food safety issue has become increasingly important worldwide (Blidariu and Grozea, 2011). Efforts have been made to minimize the negative effects of food production systems on our environment. Nevertheless, there seems to be an urgent need to develop sustainable aquaculture and agriculture in the near future.
(Klinger and Naylor, 2012; Stankus, 2013; Turciós and Papenbrock, 2014).

However, the food production patterns of currently mainstream worldwide are defective which are wasteful, pollution-carrying and unsustainable. Hence, the food industries are facing great challenges. This article aims at reviewing how wetlands could be integrated with food production processes via ecological approach, along with a dual purpose of pollution control and safe and quality production.

1.1. Food security

It is commonly recognized that food security is the greatest challenge to sustain human standard of living in the 21st century (UN, 2009), because of rapid population growth, which the increase in global population has been projected to reach 8.3 billion by 2030 (National Intelligence Council, 2012). In addition, more than one billion of the present global population of 6.8 billion is under-nourished (Mustafa, 2010). It is envisaged that global food production will have to increase by at least 40% over the next 2 decades to meet the ever increasing food demand (FAO, 2006).

The way to feed the global population equitably and sustainably is in fact a great challenge in the near future (Hill and Mustafa, 2011).

1.2. Environmental pressures

According to the assessment made by the World Wildlife Fund, overuse of the planet’s natural resources has reached an alarming level, with human demands on natural resources doubled in the last 50 years. The WWF’s ‘Living Planet Report’ states that global consumption of resources is 50% above Earth’s sustainable ability (WWF, 2010). Furthermore, major pressures are exerted on the environment, due to continued consumerism in developed countries and growing affluence in a number of emerging economies. These led to an even higher demand of natural resources (Rockström and Karlberg, 2010). Therefore, it is rather difficult to ensure sufficient food and water for all to sustain livelihoods for present and future generations (Hill and Mustafa, 2011).

Climate change also plays a profound role in various food production processes. For example, the impacts of global warming on harmful algal blooms may affect the quality and safety of the aquatic products (Hallegaard, 2014). Besides, extreme changes in climates are observed more frequently in recent years worldwide and aquaculture and agriculture are seriously affected by these extreme weather, such as severe storms, tornados, salinity intrusions, droughts and floods (Sutradhar et al., 2015). Rising sea level can affect aquaculture in coastal areas and cause salinity intrusion into delta which can also affect freshwater aquaculture (Edwards, 2015; Sun et al., 2015). Although efforts (such as alternative to the burning of fossil fuels, targets and agreement on reducing the carbon dioxide) have been made by developing technologies to assist sustainable development, the rate of development is insufficient to ease the immediate threats of climate change (Hill and Mustafa, 2011; Woulhouse et al., 2015).

Water and soil loss, soil desertification and salinization, water eutrophication and among other factors are threatening agriculture and aquaculture in varying degrees. These environmental pressures are aggravating their effects on food production, and the range of influences has been enlarged by overlapping influences. As a consequence, the normal ecosystem functions and services of our food production systems have been degraded (Rockström and Karlberg, 2010).

1.3. The threats of environmental pollutants

Apart from excessive nutrients such as nitrogen and phosphorus, which can cause eutrophication in water, elevated concentrations of a wide range of persistent toxic substances (PTS), including heavy metals (such as mercury (Hg), chromium (Cr), lead (Pb)), persistent organic pollutants (POPs such as DDT) and certain emerging chemicals of concern (such as flame retardants) found in soil, water and air worldwide during the past decades, are greatly threatening our food production and food safety.

Despite of the success of many countries and regions of the world (such as the USA and EU) with relatively successful control and management practices for PTS, the lack of efficient control and management in this regard, especially in certain rapidly developing countries, making PTS easy to spread into environment. This situation has increased the potential poisons to human body by direct ingestion of contaminated water and consumption of food products grown in contaminated fields, and even through skin exposure and breathing air (Jane et al., 2000). For instance, the Pearl River Delta (PRD), one of the most developed regions in China, has become the world’s factory for various industries, e.g. textiles, and electrical/electronic products, and rather high concentrations of polychlorinated biphenyls (PCBs), cadmium (Cd), Pb and Hg in fish reared in fish ponds around the area have been frequently reported (Cheung et al., 2008; Nie et al., 2006; Zhou and Wong, 2000). Li et al. (2011) reported a soil pollution status of PTS in a newly developing industrial area around Bohai Bay, Tianjin in Northern China that relatively high concentrations of DDT (varied from ND (less than the limit of quantification) to 2417 ng/g, with a mean value of 73.9 ng/g), DCH (varied from ND to 51,299 ng/g, with a mean value of 654 ng/g) and PAHs (varied from 68.7 to 43,930 ng/g, with a mean value of 1225 ng/g) compared to most of the earlier studies in China (An et al., 2006; Hu et al., 2005; Li et al., 2008; Zhang et al., 2006, 2009) in and around the industrial area. Exposure of PTS to the local residents was associated with a higher risk of local residents’ health, such as breast cancer (odds ratio: 1.87, 95% confidence interval: 0.21–30.06), stomach cancer (odds ratio: 1.87, 95% confidence interval: 0.26–13.41), dermatitis (odds ratio: 1.72, 95% confidence interval: 1.05–2.80), gastroenteritis (odds ratio: 1.59, 95% confidence interval: 0.94–2.68), and pneumonia (odds ratio: 1.05, 95% confidence interval: 0.58–1.89).

Most of these PTS are non-biodegradable, and could be bioaccumulated and biomagnified in aquatic food chains, which could then subsequently impose health effects on consumers via dietary intake of PTS associated with large carnivorous fish (such as swordfish and grouper). It has been observed that trash fish (small fish without high commercial value) used in fish farms as feeds in South China is often contaminated (Cheng et al., 2014; Liang et al., 2011, 2012; Zhou and Wong, 2000). It has been observed that fish meal and oil derived from trash fish served as the major components of feeds for conventional aquaculture are contaminated with DDT, Hg, and even dioxins, e.g. in USA and Canada (Campbell et al., 2005; Damsky et al., 2009). To produce products using contaminated feeds or in contaminated fields will ultimately exert human health risks, especially to sensitive members of the population, such as infants and pregnant women. Various studies revealed that PTS play a crucial role in the pathogenesis of some health effects, such as POPs, Hg with male subfertility (Hauser et al., 2003; Hsu et al., 2014; McAuliffe et al., 2012), autism in children due to metal overload (Bjørklund, 2013; Hagmeyer et al., 2015); Cancers associated with high loadings of PTS in human bodies (Cohn et al., 2007; Li et al., 2011; Steinmaus et al., 2013; Vogt et al., 2012), etc.

1.4. The unsustainable living and production patterns at present

Sustainable development involves the integration of cultural, economic, political and environmental factors (Hoff, 1998).
However, cultural and political concerns are often given ways to economic development both in the past and at present. There is also a lack of efficient educational and political guidance in developing countries. In addition, unsustainable living and production patterns have also resulted in deterioration of environmental quality for sustainable development.

To produce larger quantities of food to satisfy demand of the ever increasing population more effectively, conventional agriculture and aquaculture developed in the last decades focused on intensive production. Many food items are produced in monoculture, for cultivating and harvesting crops or animals more easily. High technological farms use compound feeds, chemical fertilizers, pesticides, hormones and confined intensive animal feeding operations, since they are perceived as the most efficient strategies to maximize the output of limited land areas or water bodies.

Heavy use of antibiotics in confined animal feeding operations contributes to the problem of AMR that would extend to affect human health (Morrissey et al., 2015; Woolhouse et al., 2015), 175,000 t of antibiotics were estimated to be produced, used and misused per year (Laxminarayan et al., 2013), and under the directional selection by antibiotic residues, the host animals contain AMR strains of bacteria may serve as a reservoir for AMR genes in other food animals (Amaechi et al., 2015; Woolhouse et al., 2015) and drive the evolution of other microorganisms (Habets and Brockhurst, 2012; Laxminarayan et al., 2013). Although antimicrobial peptides which have been proposed as a promising new class of antimicrobials and been applied as feed additives (Kogut et al., 2013; Yu et al., 2013), the new study provided the first evidence that evolved resistance to a therapeutic antimicrobial peptides can provide cross-resistance to a human immunity peptide (Habets and Brockhurst, 2012). AMR has become a global environmental problem similar to climate change (Woolhouse et al., 2015).

High fertilizer levels applied to enhance production or exploit the productive potential of crops for continuous production had resulted in an imbalanced soil nutrients and heavy use of pesticides (Richter et al., 2015; Ng et al., 2014), due to the increased yield is more susceptible to pests, and pesticides are generally used for pest control. On the other hand the natural enemies of pests are also susceptible to pesticides, which in turn, leading to more usage of pesticides. Nutrient loss through runoff is also a problem, and it has been reported that non-source point source pollution from agriculture accounts for 60–80% of the nutrient loading to rivers and lakes (Min and Jiao, 2002), and high nitrate concentrations in drinking water has been associated with methemoglobinemia and consequential cyanosis in infants (Fan and Steinberg, 1996). The pesticides used for reducing pests and weeds in conventional farms, together with the surplus of chemical fertilizer have led to negative impacts, causing biodiversity loss and eutrophication (Chau et al., 2015; Horton and Bush, 2003; Richter et al., 2015), and even threats to human health (Hu et al., 2015; Jones et al., 2015; Lebov et al., 2016; Rauh et al., 2011). There are signs of using less pesticides recently (Moore et al., 2009; O’Geen et al., 2010; Vymazal and Brezinová, 2015), but such actions have led to serious crop yield reductions (Oerke, 2006; Oerke et al., 1994).

Compound feeds with high protein contents used to accelerate the growth of food animals without efficient methods to treat the residues are known to cause ecological hazards (Edwards, 2015; Zhang and Fang, 2006). Approximately 5.44 t of nitrogen and 0.86 t of phosphorus (per hectare) are released to the environment, from intensive striped catfish farming (Bosma et al., 2009; De Silva et al., 2010; Phuong et al., 2010).

These high-efficient conventional food production patterns which exploit the potential production, without sufficient concern about the negative impacts on the long-term ecological and human health, are unsustainable to our planet. The more production we achieved, the more natural resources are exploited, leading to higher impacts on ecological and human health. Fortunately, some sustainable production techniques are becoming popular to ratify the conventional production systems: sustainable agriculture/ aquaculture, organic farming (Paull, 2015), regenerative agriculture, biodynamics farming and permaculture (Koepf, 2014; Nandal and Kumari, 2015; Olsen, 2014; Poincelot, 2012; Rhodes, 2012; Paull, 2015), all aiming at sustainable production, paying more attention to the balance of nature resources and human activities in food production, utilizing regenerative production resources, and producing safer food with less impacts on the ecosystem.

There seems to be an urgent need to produce safe and quality food, which is environmental friendly. To achieve this, it is necessary to explore possibilities by means of technological innovation, and reformation of production patterns, based on the combination of suitable technologies and efficient management methods.

1.5. Inspiration from nature

In nature, all the materials can be cycled and used. However, over exploitation of resources and the amount and types of waste generated by human beings have disturbed the natural balance. Hence, facilitating certain wastes as resources in food production is an essential key to sustainable development. Proper treatment and disposal of an ever increasing amount of food wastes generated from densely populated cities such as Hong Kong is a recent environmental concern. Recycling food wastes into feeds to ensure safe and quality fish production seems to be feasible, which could also partially ease disposal pressure and save natural resources (Cheng et al., 2014).

Water plays a significant role in food production, especially in aquaculture. However, water is also the major medium for diffusion of PTS, introducing PTS into fish farms, affecting the culture fish, and also discharging PTS from farms and impose negative environmental impacts (Amaraneni, 2006; An et al., 2006; Fatta et al., 2007; Rouff et al., 2013). Thus, water quality and management of water are major keys linking to safe and quality fish production, which is environmentally friendly.

Known as “Earth’s kidneys” for their purification capacity, wetlands are indispensable components of the earth’s ecosystem. They are also among the most important natural habitats that support biodiversity and provide subsistence for humans. Despite the fact that wetlands occupy only 6% of the earth’s surface, they support approximately 20% of all living organisms on earth (Zhao and Song, 2004). With the annual production value of 45–160 times (product value in terms of dollar value) of farmland ecosystems, wetlands are in fact the most productive ecosystem (Zhang, 2001).

2. Integrated wetlands for food production via ecological approach

Many wetlands are used for food production, for instance, mariculture, pond aquaculture, and plantation of crops. There exists great potential for integrating different food production systems into wetlands, in order to enhance sustainable food production, taking advantage of its ecological multifunction. These functions includes water conservation, runoff regulation (Beutel et al., 2013; Lizotte et al., 2012; Ludwig and Wright, 2015), peat accumulation, carbon sequestration (Kleinen et al., 2012; Tuittila et al., 2013), pollution purification, toxic substance transformation (Paing et al.,
2015; Sudarsan et al., 2015; Vymazal and Brezinová, 2015), and disaster prevention for both droughts and floods (Li et al., 2013; Wassens et al., 2011). Some wetlands are used for or linkage to different types of food production, based on their unique characteristics. Studies show that wetlands integrated with other systems for food production processes are able to achieve more sustainable food production (please refer to cases below for details).

2.1. Cases of integrating wetlands for food production

2.1.1. Integrated wetlands with animals

Wetlands, like paddy fields and cane shoots (Zizania latifolia (Griseb)) fields are artificial surface flow systems, generally consisting of water on the surface, with cultivated commercial aquatic crops. Higher economic benefits have been achieved through ecological approaches via integrating with appropriate animals in these modified flooded fields. Rice-duck (Wang et al., 2003; Yang et al., 2004; Zhen et al., 2007), rice-fish (Cruz et al., 1992; Suloma and Ogata, 2006), rice-crab (Yan et al., 2014), and rice-prawn (Nair et al., 2013) farming commonly practiced in Asian countries are recognized as sustainable systems using less fertilizer and pesticide. The paddy fields or cane shoot fields provide shades, shelters and organic matters for the animals, which in turn oxygenate the soil and water, consume pests and favor nutrient recycling. These animals, especially the fish and duck are also viewed as a tool within an integrated pest management (IPM) system to make the agricultural activities more sustainable and environmentally friendly. Berg (2001) reported that approximately 65% of pesticides was decreased by the benefit of IPM on rice-duck farms during 3 years, whereas non-IPM farms had increased the amount of pesticides used by 40%. These farming patterns help the farmers to increase the revenue by limited fields. It is reported that net revenue increased from the rice–fish system over the rice monoculture ranged 5%–11% in West Africa (Ofori et al., 2005), 47%–66% in Indonesia (Dwoijana and Mendoza, 2006).

Rice-fish farming system has been listed by the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) as one of the Globally Important Agricultural Heritage Systems (GIAHS), with Qingtian County of Zhejiang province of China selected as a pilot conservation site (Lu and Li, 2006). Rice-fish farming has been practiced more than 1700 years in China and the practices in other countries only began after the mid-nineteenth century (Java), mostly in the last century (such as Japan, Thailand) (Little et al., 1996), and African countries in recent years (such as Egypt, Nigeria) (Ofori et al., 2005; Suloma and Ogata, 2006).

Similar to rice-fish farming, rice-duck, rice-crab, rice-prawn farming makes use of the symbiotic relationship between paddy fields and animals to more effectively utilize nutrients and energy, reduce chemical fertilizer and pesticide inputs, increase food safety and productivity, and also mitigate the pollutants discharge (Wang et al., 2004; Zhang et al., 2001; Zhen et al., 2004). Besides, it is reported that co-culture animals in wetland fields, especially organic co-culture patterns, could effectively improve quantity and composition of soil carbohydrates (Nair et al., 2013; Yan et al., 2014; Yang et al., 2004) that would conduct to sustainable use of the soil resources.

Traditional low input rice-animal farming releases less nitrogen into environment, but the yield is limited. Thus, some conventional patterns are invoked to boost yield in most of these practices (Edwards, 2015), such as using chemical fertilizers, pelleted feeds and chemical pesticides. However, increasing feeds or fertilizer use in rice field would also reduce the nitrogen use efficiency. Hence, appropriate management of additional input would be necessary. Hu et al. (2013) indicated that fish yield can be increased in traditional rice-fish farming system without increasing nitrogen (N) pollution and without decreasing N use efficiency, and rice yields. This could be achieved by managing the ratio of feed-N to fertilizer-N that quantities N input (with a constant input rate of 120 kg/ha). A balance will be reached with 37% fertilizer-N and 63% feed-N, while N not used by rice can be used by phytoplankton or other primary producers in the field that are subsequently consumed by the fish.

2.1.2. Integrated dike-pond system

There are well-developed human-livestock-crop-fish production systems in China, based on efficient waste recycling techniques (Delmond et al., 1980; Edwards, 2009). Mulberry-dike-fish pond is one of the GIAHS (Altieri and Koohafkan, 2004) and the best known integrated production model. Mulberry trees are cultivated on the pond dikes, with leaves fed to silkworms. Excreta and pupae of silkworms are added into fishponds serving as fertilizer and fish feeds respectively, and the fertile pond mud consisting of fish excreta, organic matter, and chemical elements is brought up regularly from bottom and applied as fertilizer for the mulberry trees (Zhong, 1982; Ruddle and Zhong, 1988; Wong et al., 2004). These principles of dike-aquaculture have been modified and now widely with many sub-units of ditches and stagnant waters to suit different regional needs (Korn, 1996). Accordingly, assorted dike-pond and canal-dike agroecosystems have emerged throughout Asia.

The types of crops growing on the dikes are often governed by market demand and requirements of pond input. In early days, mulberry dikes, sugarcane dikes, fruit dikes, and miscellaneous crop dikes (such as soy-bean (Glycine Max), peanut (Arachis hypogea), carrot (Daucus curuto) were popular in Pearl River Delta (PRD). The principal commercial crops cultivated were mulberry, sugarcane and various fruits (especially litchi (Litchi spp.), longan (Dimocarpus spp.), and bananas (Mus spp.). A wide variety of vegetable crops are intercropping, inter-planting and rotation on the dikes, based on characteristics of different species, and under continuous cultivation. These vegetable crops and also some grasses are planted on all available spare land, including the dike slopes, roadsides, around the settlements, and along the watercourses. Those are the fundamental components of a dike-pond system, providing essential food for domestic use as livestock and fish feeds, and vegetables for home consumption and marketing (Ruddle et al., 1983).

The fish ponds normally raises several different compatible fish species (mainly of the carp family) at the same time. In this polyculture system, each fish species possesses distinct feeding habits, based on their physiology and morphology, occupying a different trophic level within the pond. There are also other aquatic organisms (such as carps and shrimps) thriving in the same water body. Within the same pond, different living organisms are in proximity of each other, connected by nutrient and energy transfer through water. This so called “integrated multi-trophic aquaculture (IMTA)” is in fact a diverse and low-cost approach to waste treatment, combined with efficient ecological management of aquaculture (Klinger and Naylor, 2012). The harmonious structure of this system could be achieved through appropriate selection of different fish species and their optimum stocking ratios through the experience gained by fish farmers in the past (Turchios and Papenbrook, 2014). In PRD, it is common to co-culture bighead, silver carp, grass carp, black carp, mud carp and common carp in the same pond, with grass carp as the principal species, accounting for 50% of the fish. Grass carp is the main breeding object which is mainly fed with grasses, sugarcane husks, leafy vegetables and macrophytes grown on dikes or adjacent water bodies and those plant material constitutes 99.6% of fish feed, additional feeds made up food consisting of the fermented residues of soy-bean curd, soy-bean cake, peanut cake
and rice bran. The bighead and silver carp are fed by naturally grown plankton which favor the nutrient-rich water. The common and mud carp are detritus feeders which consume excrement, unconsumed food, snails and worms (Zhong, 1982).

Apart from the typical production model of mulberry-dike–fish pond, there are several secondary production models that coexist with these integrated dike pond systems. Different domestic animals, such as rabbits, chickens and goats are reared on the dikes; while ducks on the pond water. Furthermore, aquatic plants such as duckweed, water lettuce and water hyacinth are kept in rivulets, canals, and associated bodies of water for feeding fish and pigs. Pond mud is used to cultivate mushrooms while the off-season for silkworm in winter and the nutrient-rich mud-bed is also used to fertilize the dike after the final crop of mushrooms have been harvested (Zhong, 1982). The by-products and manures from pigs and chickens are used to generate biogas; and the biogas residues are used as fish feed and fertilizer (Jiang and Zhao, 2011).

These integrated agriculture-aquaculture systems are excellent examples of sustainable aquaculture, where energy is fully utilized and most if not all elements derived from waste materials and by-products are efficiently recycled. Furthermore, all the living organisms are designed to co-exist harmoniously in this artificial ecosystem and kept balance on the resource utilization and the amount of different species. On the contrary, the conventional fish farming methods are less sustainable in terms of resource utilization. Large amounts of nutrient-rich wastewater, containing chemical residues such as antibiotics and disinfectants are produced, together with unconsumed fish feeds and excretion, imposing harmful effects on the receiving environment (Klemenčič and Bulić, 2015; Konnerup et al., 2011; Silvester et al., 2015; Richter et al., 2015; Avant, 2015; Tonguthai, 2000). Unfortunately, the area dike-ponds has continued to decline in recent years, given way to factories, residential buildings and other facilities gradually, following the economic reforms of South China started in 1978 (Wong et al., 2004).

2.1.3. “Aquaponic” (aquaculture + hydroponics) system

“Aquaponic” system is an approach which integrated intensive aquaculture with innovated agriculture technologies, with crops growing in liquid without soil (hydroponic culture). This is basically a water re-use system (Diver, 2000; Graber and Junge, 2009; Nichols and Savidov, 2011). “Aquaponic” has become a fast-growing industry in Australia (Lennard, 2004), as the lack of freshwater is a major limit for aquaculture.

2.1.4. Constructed treatment wetlands invoked for effluent treatment

Constructed treatment wetland (CTW) is an artificial wetland which is able to utilize natural functions of vegetation, soil, and microorganisms for treating wastewater, including municipal or domestic sewage, industrial and agriculture wastewater, landfill leachate, and stormwater runoff, which has been proven to be a well-established and cost-effective method (Turcius and Papenbrock, 2014; Webb et al., 2012). It is regarded as a low cost, and a low carbon method for wastewater treatment and has been applied in food production processes. For instances: CTWs have been used to treat the wastewater from animal husbandry (Hammer et al., 1993; Lee et al., 2014; Niu et al., 2015) and aquaculture (Lin et al., 2002a; Schwartz and Boyd, 1995), and non-point source pollution from agriculture (O’Geen et al., 2010). It has also been applied to lower heavy metal bioaccumulation (Cheng et al., 2002; Guittionny-Philippe et al., 2014; Yadav et al., 2012), and mitigate the use of hazardous pesticides (Kohler et al., 2004; Krone-Davis et al., 2013; Vymazal and Brezinová, 2015).

A simple integration of CTW into a recirculating hatchery was conducted by Burič et al. (Burič et al., 2015) in the Czech Republic that different from traditional RASs which generally involve specialized technologies, such as microsieve filtration, ozonation, and UV sterilization (Azaizeh et al., 2013; Good et al., 2011; Sharrer et al., 2010; Terjesen et al., 2013). This study indicated that CTW integration has the potential to increase production (potential final biomass with CW use was estimated to be 40% greater than without CW use) of a recirculating hatchery without added operational or environmental costs.

For mariculture, Webb et al. (2012) demonstrated that CTWs planted with Salicornia spp. for the treatment of effluents from land-based intensive marine aquaculture farms, and Salicornia can be sold as an agricultural crop.

However, it requires a relatively extensive area to build CTW systems sufficient for effluent treatment (Stark et al., 2015). In order to remove major pollutants from catfish, shrimp and milkfish pond effluents, a CTW with the size of 0.7–2.7 times the pond area for treating the polluted fishpond effluents would be needed (Lin et al., 2002a; Schwartz and Boyd, 1995), with the following hydraulic conditions: a low hydraulic loading rate (HLR) ranging 0.018–0.135 m day⁻¹ (Lin et al., 2002a; 2002b), and a long hydraulic retention time (HRT) ranging 1–12.8 days (Sanskayuth et al., 1996; Schwartz and Boyd, 1995). According to Shipgel et al. (2013), about 10,000 m² of CTW with Salicornia are required to remove nitrogen and total suspended solids produced from 900 kg of 45% crude protein fish feed (11 m2 kg⁻¹ of feed) during one year.
Nevertheless, most of the food production systems lack spared land to build a sufficiently large CTW. Hence, to integrate CTWs with food production systems more compact designs would be essential, especially turning CTWs into food production fields would be more practical than single function of wastewater treatment.

2.1.5. Agriculture in water (Chinampas, Floating gardens/islands)

Different from the CTWs that build on land, agriculture in water is implemented on water surface, using it as a culture medium for agriculture. This method called “Chinampa” in the early agriculture in Mexico while the Aztecs cultivated agriculture islands as early as 1150–1350 BC. Plants are cultivated on stationary islands (by staking mud, lake sediment, and decaying vegetation out of the shallow lake bed and fencing in the rectangle with wattle) or movable islands (artificial floating islands, also called “floating gardens”) in lake shallows. The build-up layers of vegetation are raised 50 cm above the water level, making the Chinampas like sponges of organic earth that achieved the effective use of water surround them (Ruiz et al., 2014). Waste materials dredged from canals and surrounding cities were used to irrigate the plants. Flood tolerant trees are often planted at the corners to secure the Chinampas (Turcios and Papenbrok, 2014). Fish are raised in the canals forming islands in proximity, and the sedimentary waste from fish is collected to fertilize the crops planted on the islands. These Chinampas produce very high crop yields with four or up to seven harvests a year (Tuerenhout, 2005; Turcios and Papenbrok, 2014).

A new floating garden technology is developed in Bangladesh (Irfanullah et al., 2011), to allow farmers who live in areas covered by water during wet season to grow food on flooded land. Water hyacinth and bamboo are used to construct rafts as floating bodies, soil and cattle manure are placed on the surface of the rafts, with vegetables planted in the soil. New rafts would need to be built every year, and the old ones can be used as fertilizer during the dry season. Gourd (Lagenaria spp.), okra (Abelmoschus spp.), groundnut (Arachis spp.) and leafy vegetables are grown organically in these floating gardens and provided vital food and income for the poor people in developing countries.

Floating island is a new ecological treatment technique for wastewater enriched with nutrients. It can also be used as floating garden but different in the use of modern floating body and culture medium (such as polystyrene, haycite, roseite, etc.) (Dai et al., 2006) instead of fertilizer medium like mud and cow dung. This technique has a variety of forms and is also named as “ecological floating bed”, “aquatic grassland”, and “artificial floating island” (Li et al., 2007). Besides water purification, it is also used as habitat for birds and fish for ecological restoration and protection, and for developing agriculture in water for food production (Li et al., 2007; Sang and Li, 2007). Previous studies showed both terrestrial plants and aquatic plants can be cultured on floating islands as green food or safe feedstuff. These included paddy (Oryza sativa, oryza glaberrima), celery (Oenanthes javanica), goose grass (Eleusine indica), canna (Canna indica), barnyard grass (Echinochloa crusgali), water spinach (Nasturtium officinale), vetiver grass (Vetiveria zizanioides), reed (Phragmites australis); the yields are generally higher than those cultured on land (Li et al., 2007). It was demonstrated that levels of heavy metals and nitrate contained in crops cultured in an eutrophic lake (Shahu Lake, Wuchang, China) by floating islands were safe for consumption. However, biological concentration of heavy metals and PTS would be a public health concern and the quality of products should be strictly controlled.

2.2. The potential of integrating wetlands with food production systems

Wetlands provide various essential functions to sustain the global ecosystem, and can be integrated into different food production systems mentioned above. There seems to be great potential for producing safe and quality food which is environmentally friendly, by incorporating modern practices with wetlands. This is especially true for enhancing the capabilities of nutrient recycling and water purification of the whole production system, whether it is organic farming or intensive conventional farming. Mutual benefits could be achieved by the coexistence of different components and polyculture of different animal species, fully utilizing substances and energy derived from different components. The composition of the whole system is independent of the outside environment. In fact, it is a relatively closed-system, for mitigating the negative effects derived from each of the production system and the environment. The wastes are contained, degraded and utilized, instead of spreading to the outside environment as pollutants (Fig. 1).

Integrating wetlands with aquaculture, or agriculture and animal farming through adopting different appropriate patterns are the foundation of the whole system, depending on various functions of wetlands which support energy transfer, nutrient cycling and production processes.

2.2.1. Water storage and supply

One of the most potential benefits of wetlands for integrating usages would be contribution to saving water resources. Being an indispensable medium for living beings, water is also essential during the production processes of both agriculture and aquaculture (Zhong, 1982). The integration of wetlands with food production systems would greatly enable water storage and would therefore become more self-sustained, with sufficient water supply for production processes.

2.2.2. Degradation of pollutants

Degradation of pollutants in water or wet soil is usually more effective than in dry soil, as microorganisms are more active in wet than dry condition, with a more rapid transfer of nutrients and energy flow.

In addition to external interferences, wastes, animal manure and excreta are the main pollutant sources within the production ecosystems, consisting of organic matter, ammonia, nitrite, and pathogenic bacteria. Accumulation of these substances is hazardous to both living organisms and the environment, and therefore effective degradation of pollutants in time is vital to prevent negative impacts on the whole ecosystem.

2.2.3. Energy transfer and nutrient cycling

The relationship of each component within a well-established...
and integrated production ecosystem is primarily based on efficient transfers of energy and exchange of substances (Zhong, 1982), with wastes and by-products from one species recycled to become food or fertilizers for another species. The organic wastes are efficiently degraded by microorganisms, earthworms and mollusks into inorganic matter and nutrients. Inorganic compounds in wetlands are able to supply the large amount of nutrients required by algae and higher plants (Turcios and Papenbrock, 2014).

Nutrients are recycled within food chains and food webs involving a variety of producers, consumers and decomposers which are supported by suitable habitats and conditions. In the integrated dike-pond system, the pond is the heart of this production system that produce the marketable fish. The organic residues settle to the bottom of the pond as nutrient rich pond mud, and the pond mud is excavated and used to repair and fertilize the upper surface of the dike that produce the essential inputs for the pond that demonstrated the main nutrient cycling. In aquaponics, aquaculture effluent generally contains elevated levels of ammonia, nitrate, nitrite, phosphorus, potassium, and other secondary pollutants, and also micro-nutrients applied to produce hydroponic plants (Diver, 2000).

The suitable ratio of farmed animals and plants and their associated components is important to health and stabilization of the ecosystem that determines the efficiency of energy transfer and nutrient cycling which in turn affect productivity. In mulberry-dike-fish pond system, 45% to 55% is the best proportion of dike and ponds, yielding the highest economic benefit (Ruddle et al., 1983). If the dike and pond ratio is not suitable, self-reliance between the needs from fish rearing and dike fertilization could not be achieved, and additional feeds or fertilizer may be needed (Zhong, 1982). It is known that 20 kg of grass can be transformed into 0.5 kg of grass carp and 0.25 kg of bighead carp or silver carp; while 50 kg of sugar-cane leaves can be transformed into 0.5 kg of grass carp (Zhong, 1982). These estimation indicated that 10 t of fish product would require 550 t of cattle manure, 454 t of pig manure or 75 t of duck manure, and consequently the dike-pond system will become a major sink for manure and other organic wastes (Bunting, 2013, p. 142).

3. Improvement of food production management

In general, there is a lack of effective and feasible governance tools to solve various pressing problems facing food production, especially the environmental pressures. This is especially true for environmental problems due to different PTS, threatening not only food production, but also human health. Large predatory fish such as tuna, swordfish and shark containing rather high levels of mercury, hazardous to human health (especially fetus, infants and pregnant mothers), is a typical example (Ko et al., 2012). Changes have to be made concerning the patterns of living and production. Inevitably, sustainable development is highly dependent on usages of clean/green energy which is pollution-free and renewable, and operations of clean/green industries which are non-polluting without waste generation; in addition to clean/green community and individual life styles which are with high concerns and feasible governance on the ecosystem preservation and individual development (Hill and Mustafa, 2011). This can only be achieved by proper and effective management of all input and output, including wastes of individual subsystems such as urban centers, industries and food production fields. Therefore, sustainable management of food production is linked to both sustainable agriculture and sustainable aquaculture (Hill and Mustafa, 2011). Listed below are four principles involved in achieving sustainable food production, focusing on minimal environmental disturbance and safe food production management (Fig. 2).

(1) Minimize input of hazardous substances. In view of bioaccumulation and biomagnification of various PTS (such as Hg, PBDEs, and DDTs) into the food production systems; the AMR problem caused by the direction selection of antibiotic; and other problems caused by the residues of pesticides and hormones, that have been threatening the human and ecosystem health, a better control of these inputs to the food production systems is highly essential. Integrated farms using strategies such as polyculture and co-culture are more efficient in using resources, with a higher total commercial income than monocultures (Nair et al., 2013; Ofori et al., 2005; Wang et al., 2003; Xi and Qin, 2009). However, serious problems are encountered, if PTS are entered into the production systems, and their concentrations are magnified due to bioaccumulation and biomagnification along the aquatic food chains (Scholz-Starke et al., 2013; Windham-Myers et al., 2014; Zaldivar et al., 2011). Catastrophic loss of crawfish (Procambarus clarkii) was reported in an integrated rice-crawfish facility due to the usage of pesticides for the control of rice water weevil (Lissorhoptrus oryzophilus) (Avault, 2001). Thus, strict management is needed to control the inputs of PTS during food production processes. The use of safe feeds (with low and acceptable levels of PTS), and bio-degradable pesticides without persistent toxic effects is also recommended.

(2) Minimize negative impacts on the ecosystem. This is important to maintain a healthy environment adjacent to food production systems, by enhancing the capability of pollutant treatment, especially the wastewater pathway which is the main pathway affecting the adjacent ecosystem. This could be achieved by effective waste treatment, e.g. taking advantages of wetland and biogas techniques, by improving the structure and function of the food production systems, enhancing their capability of water purification and waste management. For instance, inclusion of the components of hydroponic, constructed treatment wetland or floating islands into aquaculture could eliminate potential eutrophication problems (Dai et al., 2006; Graber and Junge, 2009; Shutes, 2001; Yeh et al., 2015).

(3) Recycle waste as resources. There is a need to recycle all

![Fig. 2. A concept framework for environmental friendly and safe food production management.](image-url)
wastes (e.g., sediment enriched in nutrients could be used as fertilizer) and byproducts (e.g. food processing byproducts such as bone and head of fish could be used as fish meal) generated as resources in food production systems, as much as possible. Minimizing inputs of hazardous substances would therefore ensure safer use of these wastes and byproducts. A good management of waste recycling not only minimizes pollution discharges, but also maximizes nutrient utilization, resulting in enhanced yields and economic benefits. For instance, the mud derived from aquaculture is regarded as a good “slow-release” fertilizer in agriculture with high concentrations of organic matter, nitrogen and phosphorus, which has been used to fertilize the dikes and cultured mushrooms in the integrated dike-pond system (Bergheim et al., 1993; Westerman et al., 1993).

(4) Select high quality production sites. The selection of high quality food production site is absolutely vital to ensure safety of food products. Currently, many sites for food production, and also water sources for food production are polluted, especially in developing countries, where factories are built in the vicinity of food production farms. Thus, insulating food production sites from polluted sites would ensure higher quality production of food items, without entry of different toxic chemicals. For instance, 8000 t of red tilapia was killed in the Chao Phraya River (Thailand) in 2007, due to the clandestine and illegal release of untreated factory effluents (Pongpao and Wipatayotin, 2007).

4. Food safety and risk control

In rapidly developing countries, the main safety risks for a food production system include pathophoresis, raw or improperly treated wastewater for irrigation, entry of pesticide residues, heavy metals and other PTS into food production systems, from contaminated soils, water, and air, resulting in accumulation of these substances in the cultured products, imposing subsequent health risks, e.g. autism is linked with body metal overload, with children who have high consumption rates of fish contaminated with mercury (Ko et al., 2012).

Unfortunately, the use of trash fish for feeding carnivorous fish species, and even the commercial pellets containing fishmeal (also made of low quality fish processing waste) is also the major sources of PTS, entering into the cultured products (Liang et al., 2012). In addition, the use of food supplements such as hormones and antibiotics for enhancing fish growth should be more strictly regulated and managed (Jeong et al., 2010), but it is difficult to regulate and manage such behaviors”.

In addition to adopting safe food production management mentioned above to inhibit entry of PTS into the food chains, non-chemical methods should be used for controlling pests and diseases, i.e., biological control (resistant cultivars, predators, antagonistic organisms) or physical control (barriers, traps, manipulation of the environment) (Chalmers, 2004). In this regard, farming indoor would require fewer pesticides and fertilizers, which could reduce human health risks associated with high exposure to agrochemicals, comparing to open conventional farming (Graff, 2009). In fact, isolating the production sites from the pollution sources, such as air emission and waste effluent from various industries is absolutely necessary to ensure safe and quality products. For ground-based urban farming, a minimum distance is recommended between production fields and main roads to reduce the contamination of crops by lead and cadmium (Säumel et al., 2012). Suitable buffer zones should be considered as one of the components in these production systems in order to minimize potential harmful effects.

There have been public health concerns about the potential risks from integrated animal-animal system recently, due to outbreaks of virulent strains such as H5N1 avian flu, when different kinds of animals are reared in close proximity (Bunting, 2013). In view of this, potential mutation of virus within one kind of animal into a more virulent strain should not be overlooked, as it will be more readily be transmitted from human to human. Therefore, the type of animals to be included in the integrated system should be carefully chosen, and the possible interaction between different types of animals grown together should be carefully monitored.

However, pigs and poultry have been raised together on farms in Asia and Europe for centuries (Edwards et al., 1988), and there has been no evidence for the transmission of viruses to humans, mediated by such production strategy in the past. However, when compared to the past history, the outbreak of virulent strains has become more frequent. These included H5N1 avian flu, Severe Acute Respiratory Syndromes (SARS), Swine influenza virus (SIV) and Middle East Respiratory Syndrome (MERS). This is likely caused by the differences in terms of food production patterns between the past and present. Rearing livestock in pens, especially under intensive farming, restricts the activity of livestock. Con-tinual application of medications and disinfectants to maintain low pathogenic environments may have reduced the immunity of livestock and enhanced the tolerance and infectivity of pathogenic organisms. In addition, a large proportion of human population is having from many types of unhealthy habits (such as eat unhealthily, lack of exercise, irregular schedule of work and rest, live with oversize pressure), resulting a sub-health condition with low resistance, rendering themselves to become more susceptible. There were evidences of correlation between agriculture intensification and biodiversity loss and possible influences on disease emergency (Morand et al., 2014; Thongsripong et al., 2013). Thus, researches should put more focus on the therapeutic thought of increasing the resistance first, instead of extensive application of antibiotics and disinfectors.

Considering the recycling of waste produced by an animal species to another as resource, especially the excrement which may contain pathogenic bacteria and viruses, it is suggested to use wetlands for minimizing the risks. Wetlands can treat wastewater effectively, converting animal waste to plant biomass, which can be used as feeding materials for rearing animals. Wetlands are known for their high efficiency in pathogen removal (Wu, 2008). Furthermore, rotating different plant species at certain time intervals is effective on reducing diseases (Zhong, 1982), and ensuring safety of food products (Specht et al., 2014).

5. Strategies of integrating wetlands with food production

Agriculture and aquaculture are the two main food production patterns. Organic production pattern is regarded as a more sustainable farming system than conventional pattern, in terms of conserving soil, water, energy and biodiversity (Gabriel et al., 2013; Pimentel et al., 2005), although it is less sustainable in producing the required food for the growing population in order to satisfy the increasing demand for food, conventional production pattern is still indispensable, but improvements to enhance food safety and environmental protection are essential. Urgent solutions are needed to address the issue of PTS entering into the production systems, and also waste materials (animal wastes and nutrients) escaping the systems, threatening environmental and human health.

In principle, wetlands integrated with food production are able to treat inorganic and organic residues, produce safe and quality food, and increase the variety of production by appropriate polyculture that would enhance the overall income (Chau et al., 2015).
The relatively closed-systems are more efficient in maximizing usage of resources and minimizing adverse environmental impacts. Multiple wetland techniques and functions would be contributing to these strategies which would also be contributing to vertical farming. The strategies of integrated wetlands with food production are illustrated in Fig. 3.

The organic combination of agriculture, aquaculture and wetland can form an intensive polyculture production ecosystem. A good management practice is required to assemble various adjacent food production systems (such as aquaculture, animal farming and agriculture), for sharing resources more effectively. In general, functional wetlands are mainly used to treat wastewater, converting organic waste into inorganic matter, and provision of available nutrients for enhancing crop growth. The polyculture practice can maximize total production and economic return per unit area of land in limited areas (Ruddle et al., 1983).

The highly polluted conventional production patterns could be integrated with functional wetlands to minimize the adverse environmental impacts, and enhance food production more efficiently. However, hazardous substances for controlling pests should be replaced by less harmful or harmless methods, for instance, pesticides could be replaced by ecological control (such as IPM) or biopesticides, or even some Chinese herbs. Use prebiotics or probiotics to replace the antimicrobials, as well their mixture, so-called ‘synbiotics’ (Woolhouse et al., 2015) could contribute to enhance the resistance and well-being of their host, but harmless to the ecosystem (Marteau and Boutron-Ruault, 2002; Patterson and Burkholder, 2003).

6. Outlook

Although there is a consciousness that we need to produce plentiful food for the growing population (Godfray et al., 2010; Pinstrup-Andersen, 2009), the waste of food in most of the developed areas is seriously and still with starvation in some poverty areas (Gustavsson et al., 2011; Knight and Davis, 2010; Lundie and Peters, 2005). In fact, how to feed the global population equitably and sustainably is the great challenge in the near future (Hill and Mustafa, 2011). In today, how to eat safety and health is becoming the primary concern for most of the peoples. Another hand, how to keep our lives sustainable is becoming a big topic, as our environment has been polluted, the normal functions of our ecosystem have been disturbed, and some of the production resources are depleting, such as the non-renewable phosphate rock may be depleted in 50–100 years (Cordell et al., 2009). Thus, how to produce safety food via environmentally friendly patterns would be more vital in the coming future.

Food production systems with more efficient use of resources such as nutrients, energy, land, and water and less interference from hazardous substances are able to generate safe and quality food, which is environmentally friendly. In a properly integrated food production system, nutrients and energy are continuously recycled and utilized within the system, which is also effective, in reducing pollution emissions to the adjacent environment. Integrated wetland techniques (such as hydroponic, constructed treatment wetland or floating island) with food production processes, coupled with polyculture of different fish species or other organisms (such as ducks, crabs, shrimps, and etc.), are able to promote ecosystem health, and achieve sustainability, mainly via its wastewater purification and nutrient recycling capability.

The Integration of agriculture systems with aquaculture systems is one of the important traditional practices. Small-scale integrated agriculture-aquaculture systems are still widespread and of considerable importance for rural farming in some countries such as Bangladesh, Indonesia and Vietnam (Edwards, 2015). Nevertheless, some of these existing integrated agro-ecosystems
are not completely in conformity with safe food production management, or considered as environmentally friendly. Some may lack of control on waste and effluent or without proper waste and wastewater treatment, resulting in eutrophication of receiving waters. Some may lack of quality control on the additional inputs, such as using feeds contaminated with DDT and Hg. Moreover, some may lack of suitable management to isolate the production systems from the pollution sources, such as using raw and improperly treated wastewater for irrigation, uptake of pesticide residues, heavy metals and other PTFs derived from contaminated soils, water, and air. Hence, smarter plans for operating the holistic production system would be important and meaningful in order to achieve sustainable living and industrial production patterns.

Future studies need to be provided a balanced diet to different species for maintaining a local ecological balance, finding cure to diseases using harmless techniques, raising overall production, and preventing disease dissemination among animals, especially in regions of different climatic conditions. Furthermore, the government should formulate political guidance to promote the transform of environmentally unfriendly conventional food production systems into environmentally friendly integrated food production systems and also provide the needed technology and knowledge support.

Furthermore, both the national governments and relevant departments of the United Nations should conduct political guidance to promote the transform of environmentally unfriendly conventional food production and also provide worldwide support of technology and knowledge. For instance, concerns about development of antimicrobial resistance and about transference of antibiotic resistance genes from animal to human microbiota, the European Union has forbidden the use of antibiotics in livestock feed in 2006, consequently, relevant guidance was issued by World Health Organization (WHO), the Food and Agricultural Organization of the United Nations (FAO), and the World Organization for Animal Health (OIE) (Castanon, 2007).

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