Possibilities and limits of wastewater-fed aquaculture

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Abstract

Wastewater-fed aquaculture offers means to treat wastewater with integrated material-flow recycling. Several goals are achieved simultaneously: production of valuable goods (food stuff, animal feeds, raw materials, ornamental plants and animals) on one side, and production of utilizable gray water (wastewater purification and hygienisation) on the other side.

The main potential of wastewater-fed aquaculture and its major advantage over conventional wastewater treatment is the large diversity of marketable products and therefore broad possibilities of income generation. The combination of the two income generating options (wastewater treatment and biomass production) is a very interesting feature and in addition complies to several global political programs (like *Agenda 21*) .

Aquaculture is facing challenges. Optimal stocking depends on biogeographical conditions (which species grow where, under what circumstances), cultural acceptance (which products are suitable and marketable) and economical conditions.

Among factors limiting the potential and performance of aquaculture are: limited growth rates of organisms, insufficient knowledge of the factors that regulate the aquatic community, the presence of toxic contaminants (heavy metals, hormones) and other undesired effects (colorations) in the wastewater. Appropriate technological tools (aeration, mixing, pumping, special basin forms) can be integrated in order to intensify certain ecological processes and increase the output of the aquaculture plant.

At the University of Applied Sciences Waedenswil, Switzerland, wastewater-fed aquaculture is a research focus since 1993. This paper summarises some of the results and insights gained during the past seven years and gives a short overview of literature.

Nature of water contamination

Nature produces no waste. Inorganic nutrients are incorporated into organic matter synthesised by plants and animals. This organic matter is metabolised or degraded upon the death of organisms by decomposers (bacteria, fungi) into carbon dioxide, water and nutrients (ammonia, nitrate, phosphate). So the circle can restart again.

Table 1 shows some categories of substances, which are normally present in water. When these substances are introduced into the ecosystem by human activities in quantities that are far above natural concentrations, they become pollutants.

Substance group	Examples	Possible effect on the environment
Organic compounds	• natural products of metabolism (carbon-compounds) • man made organic compounds (tensides, pesticides)	• oxygen depletion • chronic toxicity • acute toxicity, bioaccumulation
Inorganic compounds	• nutrients (nitrate, phosphate, other ...) • trace elements and heavy metals (Cu, Zn, Pb, Ca ...)	• fertilisation effects • toxicity, bioaccumulation
Particles (> 0.45 µm)	• wood, metall, plastic, sand, clay	• physical interference
Microorganisms	• pathogens • indicator of faecal contamination (*E. coli*)	• vectors of disease
Dissolved gases	• O_2, CO_2, NH_3, CH_4	• fertilisation effects, toxicity

Table 1: Some categories of substances found in water and their possible effects

Categories of wastewater treatment

Practically any type of water pollution can be treated by end-of-pipe solutions. But these may require high amounts of resources (energy, material, workforce) and do not represent a final solution to the contamination problem. The contamination is only transferred to another compartment where it is either less disturbing or easier to manage (for example from wastewater to sludge). Therefore, first priority in environmental protection should be given to pollution prevention and recycling of resources.

Wastewater treatment methods can be classified in different ways. Table 2 shows a classification according to their size (which depends on the degree of centralisation of sewage system) and intensity of process with some examples. In urban areas and in industrial countries, very often the sewage system is highly centralised, and sewage is conducted to large conventional wastewater treatment plants. It is important to note that extensive wastewater treatment methods, like reed beds, can be large and part of a centralised system too.

Biological wastewater treatment includes all methods that involve organisms, and emulate at least some of the processes which take place in natural environments. These methods differ in the extent by which they emulate natural ecosystems and in the biological processes that predominate. Some biological treatment methods emulate decomposer communities and degradation processes predominate (treatment with activated sludge), whereas others emulate productive ecosystems and assimilation is important (wastewater-fed aquaculture). Beside metabolisation of contaminants, organisms can also contribute to water purification by mediating physical or chemical processes in the system, like retention, filtration or flocculation.

Intensity	Decentralised with small wwt-plants	Centralised with large wwt-plants
Extensive	Wastewater garden for 10 PE	Reed bed for 100'000 PE
Intensive	Septic tank and submersed bed treatment for 10 PE	Conventional wwt for 100'000 PE

PE: Person Equivalent, wwt: wastewater treatment

Table 2: Classification of wastewater treatment methods according to their size and intensity

Only non-toxic pollutants which are biodegradable (carbon compounds) or can be assimilated (dissolved nutrients) can be successfully treated biologically.

Conventional wastewater treatment plants normally consist of mechanical pretreatment, followed by activated sludge treatment and post-treatment units. These systems solve some problems, but are also source of some new ones:

- They are usually centralised. This implies construction of long distance sewage channels. Up to 85% of total costs for wastewater treatment can be caused by sewage channels.
- They produce large amounts of surplus sludge, which in turn causes deposition and hygiene problems, especially if heavy metals were accumulated.

What is a wastewater-fed Aquaculture?

Wastewater-fed aquaculture (WFA) is a *productive* wastewater treatment, contrary to other methods of biological wastewater treatment, which are primarily based on degradation processes. Wastewater is *reused* instead of disposed of.

A wastewater-fed aquaculture is an ancient but nevertheless innovative and successful way to treat and recycle wastewater. A constructed aquatic ecosystem, consisting of one or several water bodies with an integrated food web, is charged with nutrient rich wastewater. The central aim of the system is the assimilation of dissolved nutrients into biomass. Simultaneously organic compounds are either consumed or mineralised, and in consequence the wastewater gets purified. The constructed ecosystem reflects processes of the natural environment and is thus aesthetically pleasing.

In contrast to conventional wastewater treatment plant, WFA puts strong emphasis on the quality of the synthesised biomass and produces a wide array of valuable goods and relatively small amounts of sludge (Table 3).

Wastewater-fed aquaculture therefore complies to several points of the „Bellagio Statement“ (Schertenleib et al., in this proceedings) concerning the environmental sanitation: In WFA "waste" nutrients are respected as a resource and the economic opportunities of waste recovery and use are harnessed. It allows waste to be managed close to its source and wastewater to be recycled and added to the water budget. It offers vast potential of adaptation to any local situation. It can be optimized along several dimensions, allowing different degrees of intensity.

- community-design: polyculture, modular organisation, monoculture
- human interference with community design: low (self-design), medium (biomanipulation), high ("farming")
- system design: natural systems (ponds), artificial systems with incorporation of technological elements
- alternative emphasis on most important output: recycled water, biomass

According to Table 2 wastewater-fed aquaculture can be applied in either decentralised or centralised systems of water purification. It can be extensive, like Calcutta Wetlands (Jana 1998), but also intensified by a higher input of energy and technical elements into the system, like Stensund (Guterstam 1996) and Otelfingen aquaculture plants (Staudenmann and Junge-Berberovic 1999).

Category	Some examples
Food for humans - Edible plants	High-protein algae (*Spirulina*) Water spinach (*Ipomoea*) Water chestnuts (*Eleocharis dulcis, Cyperus esculentes*) Water nuts (*Trapa, Alternanthera*) Hydroponic vegetables and herbs (*Capsicum,* basil, lettuce)
Food for humans - Edible animals	Mussels Prawns (*Macrobrachium*) Crayfish (*Procambarus* clarkii*, Astacus, Cherax*) Fish (Carp-species, Tilapia*, Clarias, Channa striata, Micropterus salmoides*)
Animal feeds	Phytoplankton (*Microcystis, Scenedesmus, Selenastrum Anacystis, Phacus, Closterium)* High-protein floating plants (*Lemna, Azolla, Wolffia*) Zooplankton (*Asplanchna, Filina, Keratella, Brachionus, Moina, Daphnia, Cyclops*) Fish-Feeds (*Earthworms*)
Raw materials	Fibers for furniture, baskets (*Eichhornia*) Cellulose for paper (*Typha*) Isolation material (*Typha*) Fertilizer (algae suspension, plant biomass) Renewable energy sources
Luxury products	Pearls (*Hyriopsis*, *Cristaria*) Ornamental plants (*Eichhornia*, *Nuphar*) Ornamental fish (Koi - *Cyprinus carpio*)

Table 3: Wastewater-fed aquaculture can supply a wide array of marketable products

Factors to consider for planning a wastewater-fed aquaculture

When deciding the appropriate wastewater treatment for a particular situation, there are no universal solutions. Every kind of wastewater (according to its composition) and every specific local situation (for example: urban/rural, socio-cultural) requires custom made solutions. Often, there are several good solutions to the same situation. Wastewater-fed aquaculture often proves to be a sustainable biological wastewater treatment method, because it is nature-like, low-tech and income-generating. But the local factors must always be taken into consideration, beginning with the first steps of the planning process.

Table 4 illustrates some of the factors, which have to be taken into consideration when planning a wastewater aquaculture using the partly contrasting examples in Europe and Asian countries.

In planning and operating a WFA, many challenges are involved:

- Optimisation and regulation of natural ecosystems
- Integration of technological tools
- Quality standards of produced goods
- Toxines and bioaccumulation

- Acceptance of produced goods

For many of the above aspects, the research is by no means concluded. Very often experimental results are lacking, and pragmatic and intuitive decisions are necessary.

	Europe	**Asia**
climate conditions	temperate	tropical to continental
land resources	limited expensive	available in rural areas low-moderate cost
labor cost	high	low
fertilizer (nutrients)	abundant	limited
main motivation for recycling	environmental concern	limited resources
demand for food (protein)	stable	growing
demand for ornamental products	high	variable, often low
conventional wastewater treatment (degradation/elimination)	well developed, widely applied	moderate know-how, limited use
productive wastewater treatment (aquacultures)	limited experiences	traditional practical knowledge exists

Table 4: Comparison of factors influencing the application of wastewater-fed aquaculture in Europe and Asia

Sanitary effects: Wastewater hygienisation.

Several studies agree that wastewater-fed aquacultures, especially the ones consisting of several ponds, have fairly good wastewater hygienisation properties. A series of 2 –3 ponds should probably be sufficient to reduce the numbers of faecal bacteria to acceptable levels. Das (2000) reported reductions from 92% to 100% of total coliforms, faecal coliforms, *Salmonella sp*. and faecal streptococci.

Again, this applies especially to systems containing plants. Seidel (1976) reported that root excretions of certain plants (*Scirpus*, *Phragmites*) can kill faecal indicators (*E. coli*) and pathogenic bacteria (*Salmonella*). Total coliform levels in municipal wastewaters applied to artificial wetlands were significantly lower in vegetated beds than in unvegetated beds (Gersberg et al. 1987).

According to Jana (1998), epidemiological studies on fishermen reveal high prevalence of diarrhoea, cough, cold and fever. However, the values were not significantly different from workers on a freshwater fish farm. Edwards (2000) concluded that it is not possible to generalize health risks of wastewater-fed aquacultures and that some systems may present a greater risk to public health than others. But: "...it is safer to consume fish cultured in a well managed wastewater-fed system than to rely on wild fish from increasingly polluted surface water" (Edwards 2000).

Some concepts and properties of wastewater-fed aquaculture

The central feature of wastewater-fed aquaculture is the recycling of nutrients.

The main improvement of WFA compared to other methods is that nutrients are recycled into utilizable biomass. Other methods of wastewater purification can perform in many aspects better and cheaper. For example: constructed wetlands are more efficient in denitrification, conventional wastewater treatment based on activated sludge is more efficient in bacterial degradation of BOD, anaerobic tanks are more efficient in metal precipitation. Nevertheless, wastewater-fed aquaculture has the greatest recycling potential. Therefore, a central issue in improving wastewater-fed aquaculture should be to increase the share of recycled nutrients.

Nutrient recycling capacity of aquaculture is determined by growth/harvest rates and by the biomass composition of organisms. (Table 5)

Although the main purpose of the traditional wastewater-fed aquaculture often is to generate animal protein (fish), the **central role of plants** has to be emphasised:

- they capture solar energy
- some of them perform nitrogen fixation
- they produce and transport oxygen into the water
- they excrete various substances, some with bacteriostatic properties, which influence hygienisation
- they provide attachment surface and create micro-regions with favourable conditions for diverse microorganisms
- they act as temperature buffers by insulation and shading
- they prevent undesirable algae growth by shading
- they can accumulate potentially problematic substances (heavy metals)
- many species can be harvested and used as food, animal feeds, roofing, insulating, construction or heating materials.

Generally, in the aquatic environment high growth rates of stocked organisms can be achieved. The plant biomass production, and therefore also nutrient elimination, is approximately one order of magnitude higher than that of consumers. Plants can generate up to 200 tons of fresh weight per hectare per year, fish 10 tons, and *Daphnia* more than 20 tons. Therefore, maximum nutrient recycling capacity per area will be approximately:

- for plants: 1 g N m^{-2} d^{-1} and 0.1 g P m^{-2} d^{-1}
- for animals: 0.1 g N m^{-2} d^{-1} and 0.03 g P m^{-2} d^{-1}

More detailed numbers are given in Table 5.

In a well managed WFA up to 40% of nutrients can be recovered as plant biomass. The rest of elimination is due to denitrification, accumulation and sludge deposition.

Achieving all the year round high growth rates in temperate climate, where many industrialized countries are, implies higher sophistication of aquaculture plants and "high-tech ecological engineering" is required.

To offset the high treatment price, products of aquaculture have to be profitable. This implies that aquaculture should produce marketable goods with high economic return. It would be waste of land and work to produce green crops for the sole purpose of composting afterwards, unless one can generate income from compost!

Nutrient recycling efficiency and economic aspects should be explicitly stated when reporting the efficiency of aquaculture system. Reporting overall purification results (effluent/influent) is not enough. Sound nutrient budgeting is an important step towards improving the functioning of aquaculture plants.

	Maximum growth / harvest rates	Growth rate	Biomass composition		Elimination by harvesting	
Organism	**kg FW / ha / year**	**g DW m^{-2} d^{-1}**	**%N**	**%P**	**g N m^{-2} d^{-1}**	**g P m^{-2} d^{-1}**
Microalgae *	(240 000)	13.0	6.0	*0.6*	0.780	0.078
Macrophyta						
Macrophyta Floating *	(150 000)	8.0	3.9	0.8	0.312	0.064
Macrophyta emerging *	(160 000)	9.0	1.7	0.3	0.153	0.027
Eichhornia sp. Otelfingen 1998		41.9			0.770	0.190
Crayfish		*(DW @ 20% FW)*				
Semi-intensive (Australia)	2000	*Þ 0.110*	*10*	*1*	0.011	0.001
Extensive (unfed) (Australia)	200	*Þ 0.011*	*10*	*1*	0.001	0.000
Calcutta Wetlands (Jana 1998)	750	*Þ 0.041*	*10*	*1*	0.004	0.000
Zooplankton						
Daphnia (**)		0.6-80.0 **	9.5	1.2	<9.0	< 0.9
DePauw and Pruder (1986)	up to 48 000	*Þ 2.64*	*10*	*1*	0.264	0.026
Otelfingen 1998		0.9	*10*	*1*	0.090	0.009
Fish						
Calcutta wetlands (Jana 1998)	up to 9350	*Þ 0.512*	*10*	*1*	0.052	0.005
Fish (Hungary)		0.4	*10*	*1*	0.040	0.004

Table 5: Average biomass composition and growth rates of some organism groups in aquaculture
FW fresh weight
DW dry weight
italics values assumed or calculated using assumptions
* mean of several values cited in literature
** range of values calculated from Berberovic (1990) and different sources

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