Advanced disinfection of wastewater ponds' effluent by UV irradiation

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Abstract Wastewater pond systems typically show an eminent natural ability for pathogen reduction. However, due to constructional and operational limitations as well as seasonal variability of pond effluents, particular microbiological quality standards often can not be guarantied, e. g. for wastewater reuse in agriculture. There is a need for supplementary disinfection. UV irradiation has been identified as an appropriate method for this purpose. Although it has so far been applied only for highly purified effluents, tests with different pond effluents prove UV disinfection to be a reliable disinfection mean. Sedimentation effects in ponds are an ideal pre-treatment through reducing helminth eggs and disruptive particles, which diminish the performance of UV disinfection. If method-specific restraints like dependence on water quality and bacterial regrowth are taken into consideration, subsequent UV irradiation at pond systems offer a promising option for efficient sewage treatment to reach effluents with low pathogen concentrations.
Keywords Disinfection, pathogen removal, pond effluent, UV irradiation, UV transmittance

INTRODUCTION

UV irradiation of highly purified effluents from conventional sewage treatment plants is a generally proven disinfection method. However, application of UV disinfection at pond systems for advanced minimisation of pathogen concentrations in pond effluents has so far been limited to rare isolated cases, due to doubts about disinfection efficiency with inadequate quality of pond effluents.

Different from the effects of natural pathogen reduction in ponds, which are well described by many authors, the knowledge about subsequent UV disinfection is still limited. Therefore the authors conducted own lab scale tests with UV irradiation of different pond effluents to investigate the applicability of subsequent UV disinfection to pond systems, e. g. to reuse the water in agriculture.

NATURAL PATHOGEN REDUCTION BY WASTEWATER PONDS

Beside the reduction of other constituents in faecal-contaminated sewage, wastewater pond systems also show an eminent physical and biological reduction of pathogens and helminth eggs.

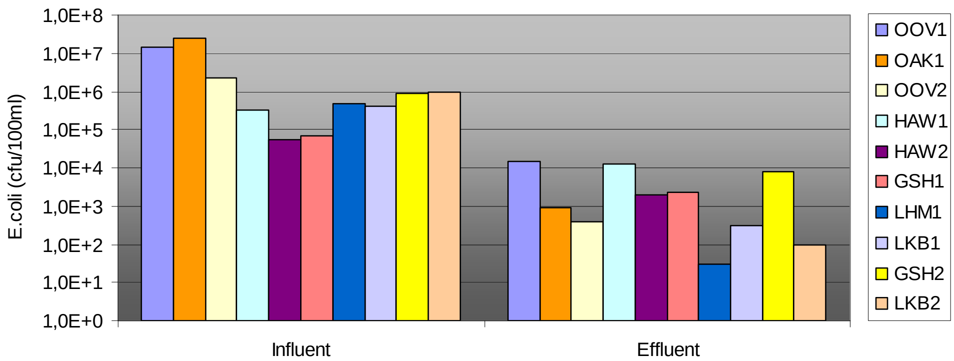

Figure 1 Escherichia coli concentrations in influent and effluent of different ponds in Germany

As displayed exemplarily in figure 1 with a comparison of influents and effluents of different wastewater pond systems in Germany (investigation in 2006/2007), even pond systems which are not especially designed for degradation of pathogens may achieve, for example, reductions of about 3 to 4 log units with bacterial indicators like Escherichia coli.

The pathogen reduction in pond systems is mainly caused by the combination of two key effects: (a) removal by sedimentation of particle-related pathogens as well as helminth eggs and (b) inactivation by insolation and biological processes (see table 1).

Table 1 Disinfection effects in wastewater ponds

Type of pathogen reduction	Mechanism
Removal	Sedimentation, which leads to a significant reduction of helminth eggs and particle-related pathogens by removal from the water body through settlement
Inactivation	High pH, especially in algae ponds, with inactivating effects when exceeding pH levels > 9
	Sunlight, resulting in different effects like photo-biological and photo-oxidative damage of DNA and external structures (e. g. see Davies-Colley, 2005)

Due to density considerations, several pathogens like bacteria do not settle as individual cells or even colonies. But typically, some bacteria adsorb to particulate matter or floc particles, which settle during sedimentation, and will later be removed with the sludge (U.S. EPA, 2004). Regarding subsequent disinfection methods, the sedimentation effects in the ponds are an ideal pre-treatment in terms of reduction of helminth eggs (up to 100 % see below) and disruptive particles.

As displayed above in figure 1, reduction rates in pond systems vary within a wide range, e. g. with E. coli between about 1.5 to 4.5 log units, depending on constructional and operational aspects like water depth, sedimentation possibility, retention times, pH value and temperature. Several approaches exist to enhance the efficiency of pathogen reduction by modification of the pond construction or advanced pond systems, as there are for example:

- specific constructions like buffers within ponds or sequent arrangement of ponds to avoid short circuits and to make sure long retention times (e .g. Shilton and Mara, 2005);
- pond-specific filter systems, like rock filters (e. g. Johnson and Mara, 2005);
- algae ponds and systems with regular high pH values for biological inactivation of pathogens.

ADVANCED DISINFECTION OF POND EFFLUENT

Despite improvements in construction and operation, disinfection effects of wastewater pond systems are regularly not sufficient to guarantee particular microbiological quality standards, as for example required for unrestricted wastewater reuse in agriculture (compare e. g. WHO 2006). In addition, pond effluents are seasonally variable, depending on the local climatic conditions. This results in the need for supplementary treatment of pond effluents by subsequent disinfection systems. By the way: this need is with other conventional mechanical and biological types of wastewater treatment plants, too.

Comparison of subsequent disinfection methods

For wastewater treatment in general, there exist a number of options for subsequent effluent disinfection. The most common ones are chlorine (Cl_2), chlorine dioxide (ClO_2), sodium hypochlorite (NaOCl), ozone (O_3), ultraviolet (UV) light, peracetic acid (PAA) and membrane filtration.

With regard to an application at pond systems, a comparison of the mentioned disinfection methods is displayed in table 2. Generally, the most inexpensive way to reduce pathogens is still chlorination, which is especially well experienced with potable water disinfection. But this method has evident disadvantages in terms of dangerous handling (toxic Cl_2 gas) and formation of harmful chlorinated organic by-products, when reacting with wastewater constituents. Ozone and membrane systems both are characterised by comparatively difficult handling as they need specific technical devices. In particular membrane technology as the latest disinfection approach is still costly compared with the other methods, and demands a high competence regarding operation and maintenance. Especially the last point conflicts with the advantage of limited operational efforts for pond plants, itself.

Table 2 Comparison of supplementary disinfection methods for pond effluent (partly from Bixio and Wintgens, 2006, and Rudolph, 2006)

Criteria	Cl_2 / ClO_2	NaOCl	UV	Ozone	PAA	Membrane
Safety	low	moderate	high	moderate	low	high
Bactericidal action	high	high	high	high	high	high
Virucidal action	moderate	moderate	moderate	mod. - high	moderate	mod. - high
Protozoa removal	low	low	high	high	low	high
Bacterial-regrowth	low	low	mod. - high	low	high	low
Residual toxicity	high	high	low	moderate	low	low
By-products	high	high	none	low	none	none
Operability	high	high	high	high	high	high
Full-scale experience	high	moderate	high	moderate	low	high
Power demand	low	low	high	high	low	High
Operating costs	low	low	low	moderate	low	mod. - high
Investment costs	moderate	moderate	moderate	high	moderate	high

Carefully considering the mentioned criterions, currently UV irradiation might be identified as most appropriate disinfection method for pond effluents. It is a relatively simple method regarding operation and maintenance with moderate investment and operational expenditures, as the same is with pond systems.

SUBSEQUENT UV DISINFECTION OF WASTEWATER PONDS' EFFLUENT

Apart from wastewater pond systems, due to the above mentioned advantages, the use of UV light as disinfectant in terms of water reuse has numerous applications, above all at small and medium scale facilities (Bixio and Wintgens, 2006). But so far it has been known as problematic in terms of high solid contents in pond effluents, which hindered a broader application. Additionally, reactivation of pathogens in UV irradiated water has to be taken into consideration (see below).

Especially about the concrete limitations for application of UV disinfection with respect to specific ponds' effluent quality, there is still little knowledge as literature reviews showed. Therefore, the authors carried out own tests with UV disinfection of pond effluents.

The performance of the germicidal effect of UV irradiation generally depends on the dose applied to the pathogens (as is the case with all disinfectants):

$$\text{UV dose [J/m}^2\text{]} = \text{intensity or irradiance [W/m}^2\text{]} \times \text{exposure time [s]}$$

UV light interacts with materials contained in the irradiated liquid through absorption, reflection, refraction and scattering. Therefore the remaining UV intensity or rather the UV dose available for pathogen inactivation is very much depending on the water constituents, especially on particles and suspended solids. There are three key parameters used to describe the influence of water constituents on the disinfection efficiency of UV irradiation:

- turbidity, stated in nephelometric turbidity units (NTU),
- suspended solids content (SS) and
- UV transmittance (or vice versa the UV absorption), as the share of light passing through a water sample over a specified distance, e. g. 1 cm.

Investigation on UV transmittance of pond effluents

For optimal UV-dose efficacy, suspended solids contents of 5 mg SS/l, turbidity levels of 5 NTU and transmittance values above 60 % are recommended (Bixio and Wintgens, 2006). As no general mathematical description of the dependence between UV efficiency and turbidity or SS has been found so far (the results have always been highly site-specific, compare e. g. Schöler, 2004), UV transmittance is the decisive parameter for design of UV irradiation units.

UV transmittance of wastewater mainly depends on physical processes like sedimentation and filtration applied to the water. Even only by extensive settlement without any further treatment, a significant improvement of the UV transmittance can be measured, as exemplarily demonstrated in figure 3 for sewage with worse initial values. As sedimentation is one of the key processes in wastewater ponds, it is no surprise to find a considerable enhancement of UV transmittance in pond effluents.

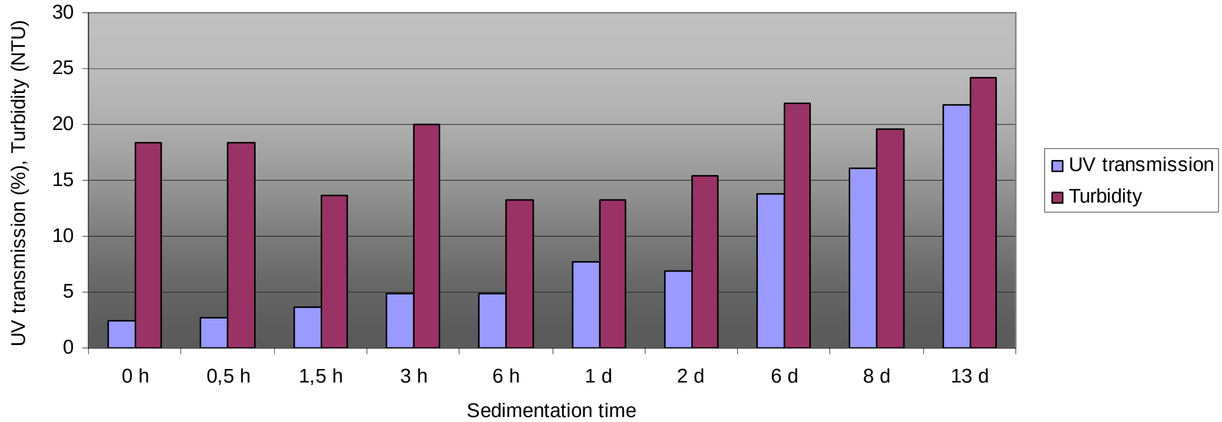

Figure 3 Development of UV transmission and turbidity over settlement time in lab scale tests

Actually, wastewater treatment by ponds show a significant effect on UV transmission values, as displayed in figure 4 with a comparison of in- and effluents of different pond systems in Germany (Rudolph et al., 2007). The range of UV transmittance is only slightly worse than that of typical secondarily treated WWTP effluents with about 45 to 70 % (Rudolph et al., 1992). Nevertheless, wastewater treatment in pond systems cannot ensure UV transmittance values over 80 % like fully purified secondary effluents after specific filtration for optimal UV disinfection efficiency.

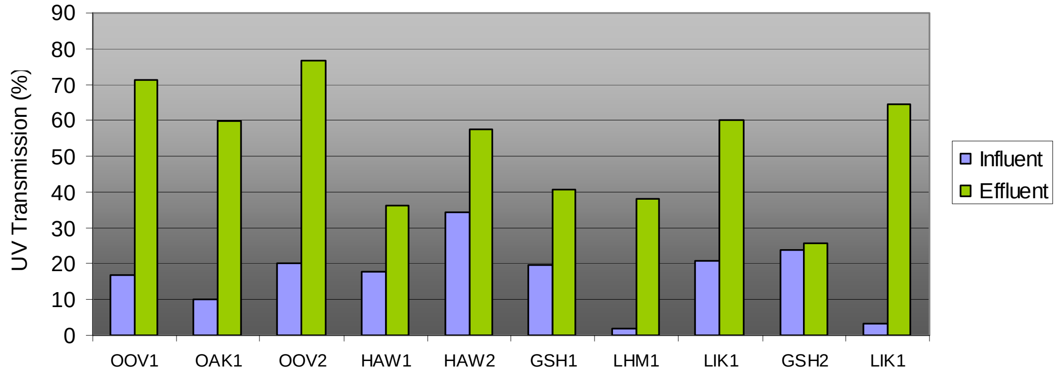

Figure 4 Exemplary comparison of UV transmittance (in %; for wavelength of 254 nm) of influents and effluents of different pond plants in Germany

Disinfection efficiency of subsequent UV irradiation

Laboratory scale tests with UV disinfection of wastewater treated in pond systems have shown that even for lower effluent qualities (= UV transmittance << 70 %) pathogen reductions with levels being adequate for agricultural reuse (e. g. E. coli values of 100 to 1000 cfu / 100 ml) are feasible with cost-effective doses. The tests were conducted by a collimated beam device according to U.S. EPA, 2002 (UV source: low-pressure mercury vapor lamps with monochromatic light output at 254 nm). As illustrated in figure 5 by generalised average dose-response curves from UV irradiation tests, the reduction rates of indicator bacteria can be found for pond effluents between mechanically and advanced biologically treated wastewater.

As an example (Fuhrmann, Rudolph, 2007): with UV doses of 500 J/m² (= 50 mJ/cm²), which are typically applied with filtrated secondary effluent to achieve a target of 10 total coliforms per 100 ml for unrestricted irrigation, a reduction to about 100 coliforms per 100 ml may be achieved with pond effluent. This means, the reduction is 1 log unit lower than that with fully purified effluent. To ensure a reduction to 10 coliforms per 100 ml, a UV dose of about 1500 J/m² (= 150 mJ/cm²) is necessary. This means, the dose has to be about three times higher than above mentioned, which is still a reliable value regarding energy consumption of the UV lamps. Depending on water quality, total costs of 0,03 – 0,10 EUR/m³ may be achieved.

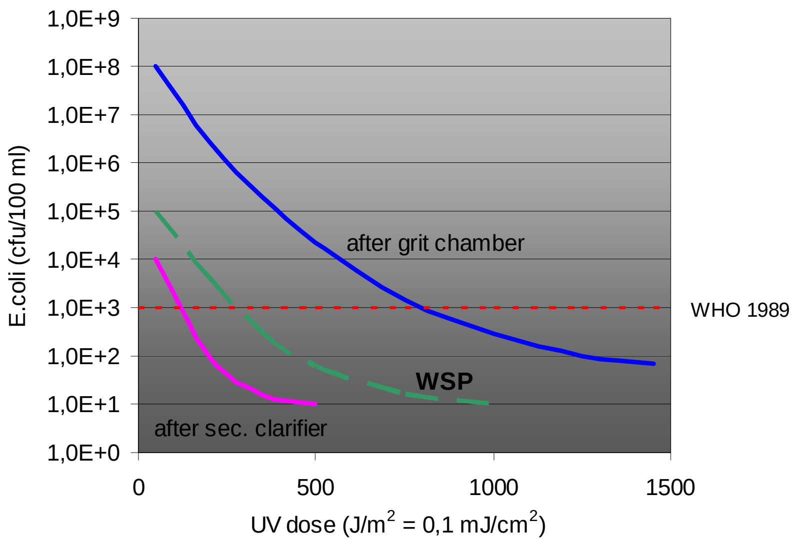

Figure 5 UV dose-response curves for different treated wastewater (Fuhrmann, Rudolph, 2007)

In total, the laboratory results show that UV irradiation is technically possible and economically reasonable for disinfection of pond effluents, even without extended further pre-treatment.

Algae Control

Like particulate constituents in the water, algae have a negative influence on UV transmittance. For regions with high insolation, it has to be taken into consideration that effluents might be heavily loaded with algae. The amounts and influence of algae depend on pond operation and effluent treatment. Therefore specific measures for algae control (removal or detaining algae from the effluent) are essential when applying UV disinfection to pond effluent in sunny regions.

Regarding the calculation of the influence of algae further research is needed (and will be conducted by the authors in 2009). No literature values could be found by the authors about the relationship of particular algae contents and the efficiency of UV irradiation. Consequently, so far there are a no clear design criteria for application of UV disinfection to algae-rich pond effluents.

Removal of helminth eggs

UV irradiation does not ensure adequate inactivation of helminth eggs. In fact, e. g. Ascaris eggs have proved to be the most UV-resistant water-related pathogen identified to date. Showing at UV doses of up to 1000 J/m^2 (= 100 mJ/cm^2), which are used for typical UV applications, the inactivation may be less than 1 log unit (Brownell and Nelson, 2006). But applied as subsequent disinfection following a pre-treatment through ponds, this effect plays only a minor role, as ponds provide high removal efficiencies of helminth eggs up to 100 % by sedimentation and accumulation in the sludge (Sperling et al., 2003). By this, ponds are a most advantageous combination for UV disinfection, closing the UV efficiency gap regarding helminth eggs removal.

Reactivation of pathogens

In contrast to disinfection by chlorine, there is no residual disinfection dose left from the UV irradiation. Repair mechanisms like photo-reactivation and dark repair of irradiated cells may let the numbers of pathogens increase again some time after the application of UV light. Therefore, it has to be taken into consideration that the pathogen reduction can be reversed when storing the UV-disinfected water for some time.

The repair effects depend on the type of UV lamp and especially on inadequate UV doses during irradiation, which is given with disinfection of not fully purified wastewater (Lindenauer and Darby, 1994). Photo-reactivation as well as dark repair effects are highly depending on the site conditions (temperature, light exposure, surfaces etc.). Photo-reactivation becomes significantly evident not before some hours of visible light exposure on disinfected water. Data of different authors show a wide range of regrowth rates, e. g. varying for reactivation of coliforms of about 1.0 to 2.0 log units for 2 to 6 hours light exposure (Whitby et al., 1984; Harris et al., 1987; Chrtek and Popp, 1991; Thyen et al., 1993, Oberg, 1995). Mostly, the maximum pathogen concentration is reached at about 1 to 2 days after UV irradiation; afterwards the concentration is decreasing again.

Because of the reactivation effects, the use of wastewater disinfected by UV light should be restricted to point-of-use applications or long-term storage.

Economic aspects

Due to relatively low construction and operation costs, pond plants offer opportunities for low-cost treatment of municipal sewage. As several comparisons of investment expenditures show, especially in rural areas the specific disadvantage of pond plants, the high place requirement per p.e., plays a minor role, because the prices for land are lower in comparison to that for necessary equipment of technical purification plants. Subsequent disinfection by UV applications requires investment costs to be found somewhere in the middle of the costs for comparable disinfection methods (chlorine, ozone, membranes), highly dependent from system scale and effluent quality (the total costs of UV irradiation are together with chlorine the lowest in comparison with the other methods, roughly about 2 – 3 time lower than ozonation and 5 – 15 times lower than membrane filtration). Summed up, the investment costs of ponds plus subsequent UV disinfection show values below the average of other treatment facilities with similar effluent quality.

As shown by above described test results, subsequent disinfection of pond effluent, e. g. for water reuse purposes, requires UV doses clearly adequate for practical applications. Depending on the required pathogen reduction, the energy consumption of the UV lamps, as the main part of the operation and maintenance efforts, is still in a feasible range, even without further pre-treatment. As the operational expenditures of pond plants are generally significantly lower than that of technical systems with higher requirements regarding maintenance and personnel competence, the arrangement of ponds with UV disinfection results in economically reliable cost levels.

Although tangible figures are difficult to name, as they are very much depending on site-specific conditions, it can be stated that in total the combination of the near-to-nature treatment in ponds with subsequent disinfection by UV irradiation appears as an economically promising solution.

CONCLUSIONS

Even if not especially designed for pathogen reduction, waste stabilisation ponds typically show eminent reductions rates of pathogens due to physical and biological treatment processes. But as the effluent is seasonally variable, and ponds as sole treatment step regularly do not fulfil relevant microbiological quality standards for purposes like water reuse, there is a need for supplementary pathogen reduction by subsequent disinfection systems. Among other options, UV irradiation has been identified as appropriate disinfection method for pond effluents.

Although UV irradiation has so far been applied only for highly purified effluents, tests with different pond effluents show UV disinfection to be a technical and economical reliable disinfection mean. Sedimentation effects in the ponds are an ideal pre-treatment by reducing helminth eggs and disruptive particles, which diminish the performance of UV disinfection. If method-specific restraints like dependence on water quality, bacterial regrowth and algae contoll are taken into consideration, subsequent UV irradiation at pond systems offer a promising option for efficient sewage treatment to reach effluent qualities with low pathogen concentrations.

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