ULTRASONIC DISINFECTION OF WASTEWATER EFFLUENTS FOR HIGH-QUALITY REUSE

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ABSTRACT

Cavitation, induced by ultrasound at low frequencies, is an effective means for the disintegration of bacterial cells. Two effects can be observed: At low ultrasound doses bacteria flocs can be declumped by mechanical shear stresses, and at increased doses ultrasound cavitation has an impact on the cell walls such that they are broken. In lab scale experiments a horn sonotrode operated at 20 kHz was run in combination with a low-pressure mercury arc lamp to treat wastewater samples taken from the effluent of a municipal treatment plant. At low ultrasound intensities a drastic change in samples' particle size distribution was observed. Consequently, subsequent UV irradiation was far more efficient as the number of large particles which impede disinfection processes was minimised by the sonication. Hence, applied UV doses could be reduced notably to obtain the same or even better disinfection effects.

KEYWORDS

Wastewater disinfection, ultrasound, cavitation, UV

INTRODUCTION

Wastewater disinfection has gained in importance recently: In general it is still not imposed by law in Europe that sewage treatment plants' (STP) effluents have to meet microbiological criteria (EEC, 1991). However, under particular circumstances wastewater effluents have to meet bacteriological criteria, e.g. for the discharge into bathing areas or for reuse purposes, dependant on the type of application (irrigation, sprinkling water in horti- and agriculturally used areas, aquaculture) (Gatel et al., 2000). An excerpt of regulations is given in Table 1.

Table 1: Microbiological requirements for bathing waters and for wastewater reuse

	Council Directive concerning the quality of bathing water (EEC, 1976)		Health Guidelines for the safe use of wastewater in agriculture and aquaculture (WHO, 1989)
Microbiological Parameters	Guide	Mandatory	Guide*
Total Coliforms / 100 mL	500	10000	
Fecal Coliforms / 100 mL	100	2000	1000
Fecal Streptococci / 100 mL	100	-	
Salmonella / L	-	0	
Enteroviruses PFU / 10 L	-	0	
Intestinal nematodes / L			1

* Reuse conditions: Irrigation of crops likely to be eaten uncooked, sports fields, public parks

As counts of indicator organisms (such as fecal coliforms) are usually not reduced to tolerable levels within a conventional treatment process (Gelzhäuser, 1989), an additional subsequent disinfection step is unavoidable. In Germany, there are some STPs at the coast of the Baltic and the Northern Sea, which are exposing their effluent to UV disinfection in summer to protect receiving bathing waters.

Generally, disinfection is applied on secondary or tertiary effluents. Using tertiary filtration has two benefits: Firstly, the concentration of particle associated pathogens, which makes up for the major number of organisms (Örmeci, 2002) is held back, and secondly, the number of particles which represent a main obstacle for the disinfectant and a shelter for the microorganisms is reduced drastically (Narkis et al., 1995; Darby et al., 1993).
Especially the efficiency of UV irradiation is affected by high concentrations of suspended matter: Studies (Sakamoto and Zimmer, 1997) have shown that large particles (about 50 µm diameter) are difficult to penetrate so that the required UV demand is raised drastically. Herwig et al. (2000) report that particles larger than 50 µm are removed efficiently in a rapid sand filter. When it comes to real-scale applications however, they suffer from various drawbacks (e.g. clogging, algae growth, backwashing). Moreover, rapid sand filters are expensive in construction and maintenance.
Another way to notably diminish the fraction of these problematic "large solids" present in wastewater is the application of ultrasound. A number of articles about the disintegration of biosolids by means of ultrasound has been published (Lehne and Müller, 1999; Nickel, 1999), and detailed descriptions of ultrasound's physical and chemical effects are available (Suslick, 1988). However, experiments with sonicated wastewater effluents are scarce. Therefore, our aim is to elaborate ultrasound's potential in this field and to find out under which conditions ultrasound is appropriate to contribute to waste water disinfection.

MATERIALS AND METHODS

The experimental set-up is depicted in the accompanying schematic Figure 1. In order to avoid sedimentation, a continuous set-up was chosen which also represents a technical system in a better way than a discontinuous system. 10 litres of treated municipal wastewater (secondary effluent of a STP with full biological treatment, COD: 30mg/L) are stored in a glass bottle and mixed constantly by a magnetic stirrer. A peristaltic pump is used to convey the medium through the system. Samples can be taken after each individual step of treatment.

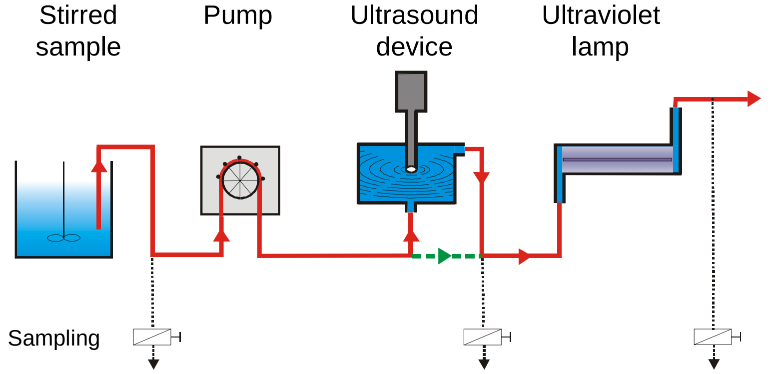

Figure 1: Flow scheme of the experimental set-up

As strongest cavitation effects in terms of hydromechanical forces can be observed at low-frequency ultrasound application (Neis et al., 2001) a 20 kHz ultrasound device ("Branson Sonifier W-450", horn sonotrode, tip diameter: 1.3 cm) was used. Electrical power in the range of 41 to 154 Watt was applied. The effective energy input into the sample was determined by calorimetric measurements. Intensities (power per sonotrode tip surface) ranged from 1.7 to 60.8 W/cm², densities (power per sample volume) ranged from 10 to 400 W/L, respectively.
The low-pressure mercury arc lamp (manufacturer: „Pureflow Ultraviolet Inc.", nominal length: 20 cm, diameter: 1.3 cm) is enclosed in a tubular processing chamber. A surrounding thin layer of quartz glass shields the lamp from the sample that flows parallel to the orientation of the lamp. Its energy consumption is 14 Watt of which 3 Watt are emitted at 254nm (37 µW/cm²@1m), the relevant wavelength for bacteria inactivation.
Particle size analysis was conducted with automatic laser scanners (Hiac Royco, model 8000A, equipped with a sampler, model 3000A and a HRLD-150 sensor and Galai, model CIS 100, respectively).
The Spread Plate Technique (for high concentrations of microorganisms) and the Membrane Filtration Technique (for low levels of detectable microorganisms) have been applied, according to the "Standard Methods for the Examination of Water and Wastewater" (APHA, 1995). For the enumeration of total germs, total coliforms, Escherichia coli, fecal coliforms and fecal streptococci, specific types of solid agar have been chosen. Results are presented as colony forming units (CFU) per 100ml.

RESULTS AND DISCUSSION

1. Ultrasonic modification of particle size distribution (PSD)

In a set of experiments wastewater samples were treated with ultrasound alone. Ultrasound's capability to eliminate the fraction of big particles is demonstrated in Figure 2.

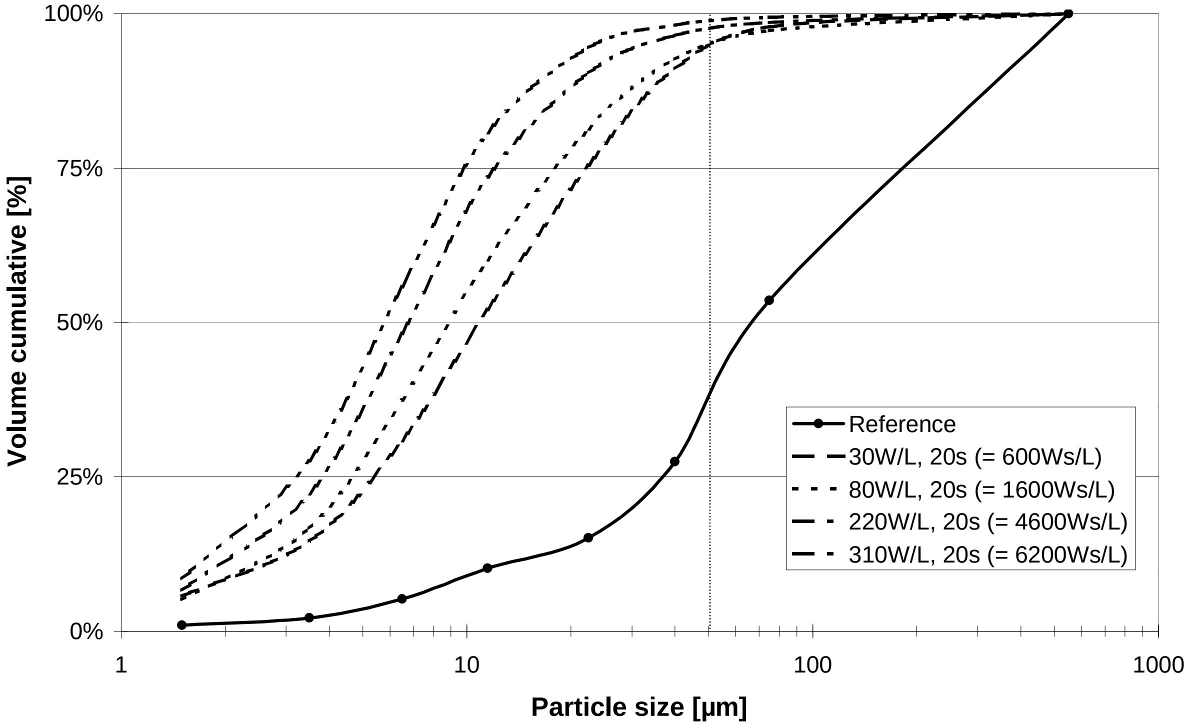

Figure 2: Effect of wastewater sonication (20 s at various densities) on PSD

In order to better demonstrate ultrasound's deagglomeration effect on suspended matter, primary effluents were treated first. These samples were treated for 20 seconds at various ultrasound densities. Having in mind that samples containing particles larger than 50µm require high doses of disinfectants, attention should be paid to the shift of samples' mean (volumetric) diameter: Initially, 63 % of the solids in the wastewater sample were bigger than 50 µm in diameter. After a sonication for 20 seconds at 30 W/L, this fraction just accounted for 5 % of the total counts. Increasing ultrasound density (80 W/L, 220 W/L, 310 W/L) just resulted in minor decreases of the mean particle size.
It stands out that low ultrasound energy (30 W/L) is already sufficient to provoke a clear change in particle composition, whereas further increased ultrasonic doses have only a marginal effect. However, all these applied ultrasound doses are too low to have an impact on bacterial counts - as they were < 0.2 log units, these results can be disregarded in context with disinfection.

2. Impact of ultrasound on microorganisms

For long sonication times (up to 60 minutes) and maximum US density applied, a significant reduction of microbial counts could be observed. Figure 3 shows that a maximum reduction of 2.9 log units of E. coli was achieved at a dose of 400 Wh/L (60 min at 400 W/L). This is in accordance with the findings of Hua et al. (2000) for fecal coliforms.

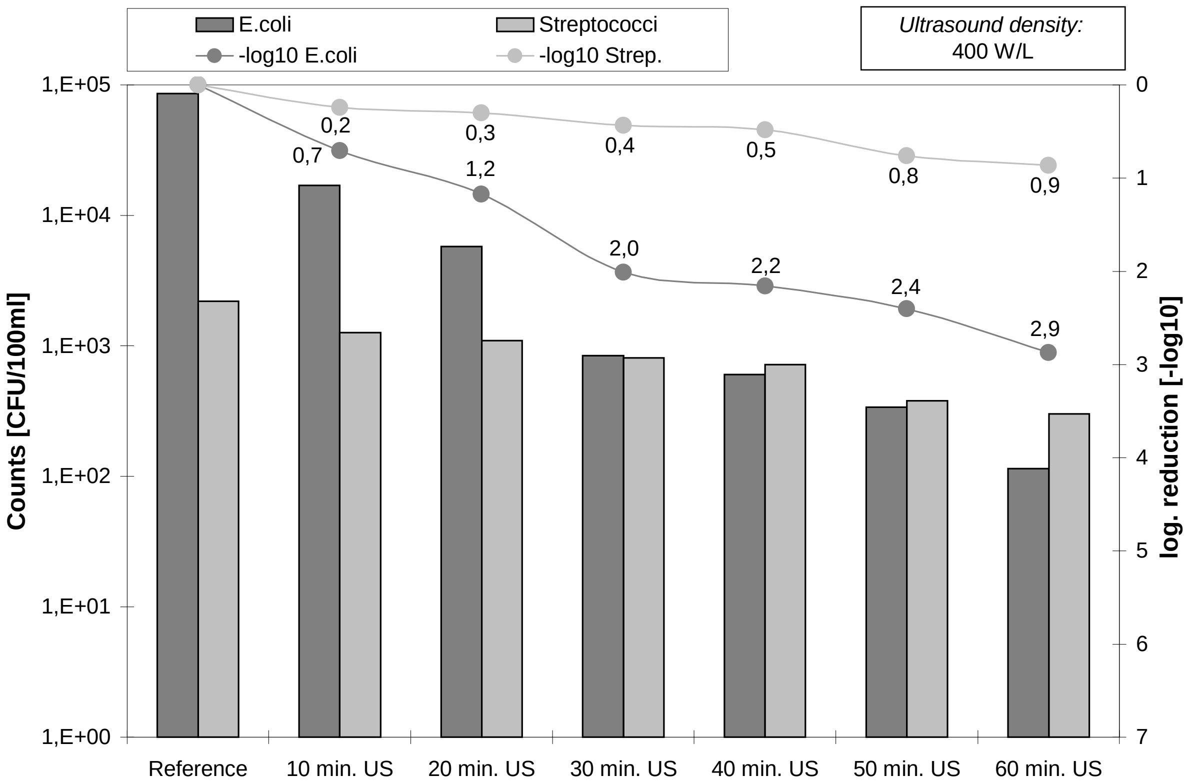

Figure 3: Effect of long sonication on E. coli and fecal streptococci

Several studies have shown that the enterococci species of fecal streptococci are a more appropriate indicator of fecal pollution than fecal coliforms as they show better correlation to human diseases and they survive longer in the water. Moreover, they are more resistant to environmental stress than commonly monitored coliforms (Figueras, 1997). For this reason the group of fecal streptococci was also analysed.

Figure 3 shows that at the applied dose fecal streptococci are significantly less vulnerable to cavitation effects than coliform bacteria. This is due to the cell wall structure: gram-positive streptococci's cell walls are notably thicker (200 Å) than gram-negative enterobacteria's (100 - 150 Å) (Cummins, 1989).
E. coli as well as fecal streptococci decay kinetics follow a first order reaction behaviour like it is usually observed with other disinfection methods. The decay rate constant k is

$$k = \frac{1}{t} \cdot \ln\left(\frac{N_0}{N_t}\right)$$

At the applied ultrasound density of 400 W/L we found the following values: $k_{E.coli} = 0.11\ min^{-1}$ and $k_{strepto} = 0.03\ min^{-1}$ ($R^2_{E.coli} = 0.96$, $R^2_{strepto} = 0.97$). One might want to compare these results with other data like for UV irradiation: $k = 0.056\ min^{-1}$ at 1 µW/cm² or Ozone: $k = 0.88\ min^{-1}$ at 0.5 mg/L (Lezcano et al., 1997). However, it must be considered that these experiments were a first set of tests with lab scale equipment. Experiences with ultrasound sludge disintegration have shown that full scale 5 kW ultrasound reactors are more efficient than lab scale models. Therefore, it can be assumed that ultrasound disinfection efficiency will be better for full scale continuous flow tests.

At this point in time however we consider a combination of short ultrasonic application followed by conventional disinfection methods also as promising both in terms of better efficiency/sustainability as well as better economy.

3. Combined wastewater disinfection

Already low doses of ultrasound changed PSD drastically and per such the protection of single microorganisms is removed. Consequently a following UV application might be significantly promoted. Having this strategy in mind, a combined ultrasound and UV method was applied on secondary effluents and the energy input was held low.

Figure 4 depicts disinfection efficiencies for a secondary effluent (TSS=5.2mg/l, mean diameter: 68µm) that was irradiated with sole UV light and with a combination of US and UV. 30 seconds of UV irradiation were needed to bring down the number of E. coli to less than 1000 and fecal streptococci to less than 100 CFU/100mL, respectively.

Ultrasonic pre-treatment for just 10 seconds at densities of 170 W/L brought down mean particle size to 35µm, with an increased US density of 310 W/L the samples' mean diameter could even be lowered to 20 µm. For both microbiological parameters observed, the ultrasonic pre-treatment has a clear beneficial effect; disinfection efficiency is by more than 1 order of magnitude higher. As expected, the thicker-walled streptococcus species seems to be less vulnerable than E. coli.

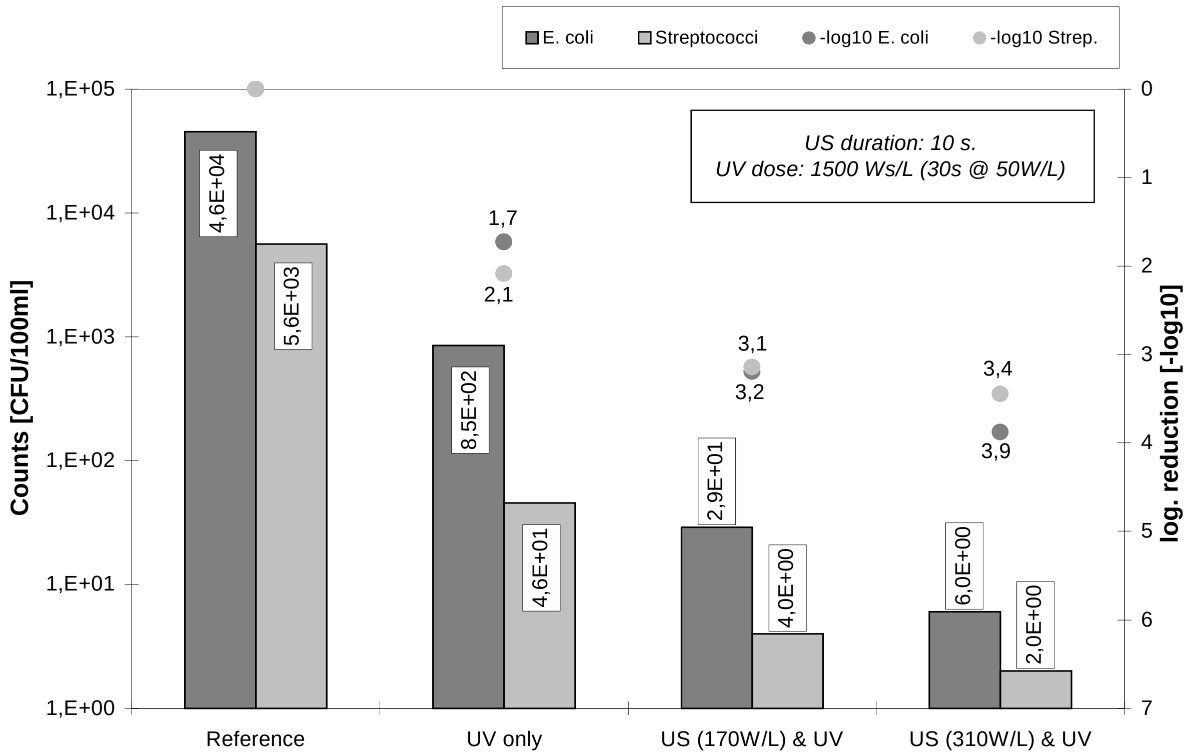

Figure 4: Reduction of E. coli and fecal streptococci by ultrasonic pre-treatment for 10 s followed by UV irradiation for 30 s

Figure 5 demonstrates that a combination of short ultrasonic and subsequent ultraviolet treatment is useful, although specific energy consumption of the US device (80 W/L) is higher than the one of the UV lamp's (50 W/L).

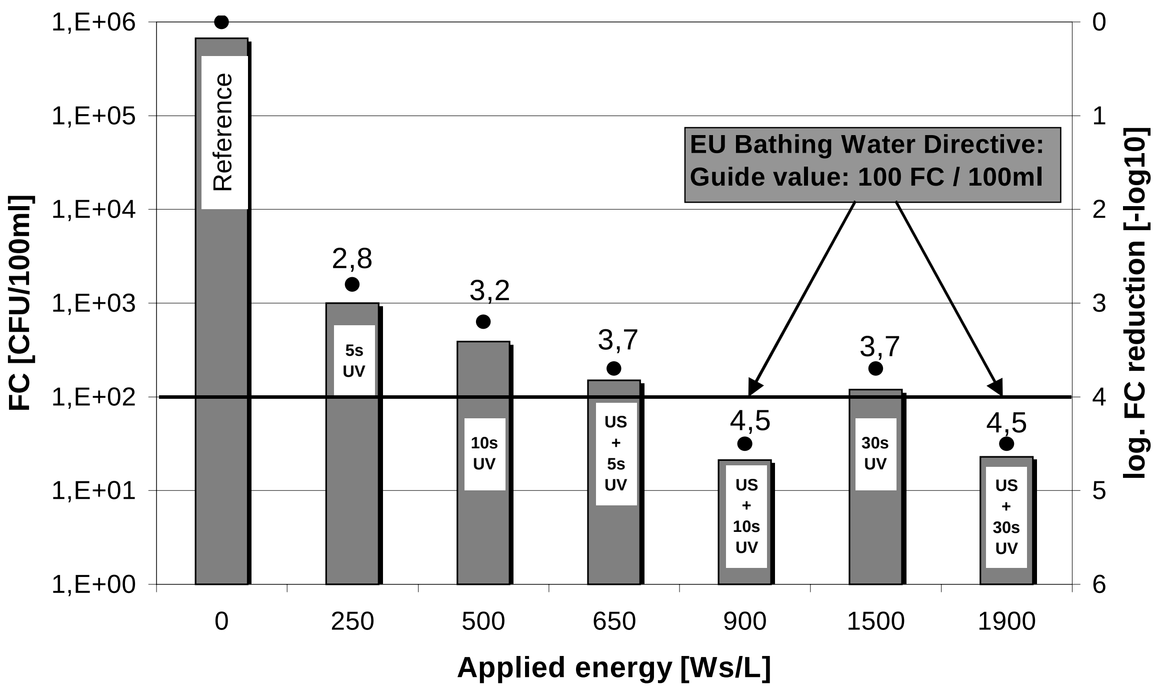

Figure 5: Improved UV disinfection (density: 50 W/L) by ultrasonic pre-treatment (sonication time: 5 s, density: 80 W/L) to meet the Bathing Water guide value (abscissa not to scale)

A wastewater sample was exposed to UV light for 5, 10 and 30 seconds with reductions of fecal coliforms of 2.8, 3.2 and 3.7 log orders, respectively. It strikes out that even ultraviolet treatment for 30 seconds is insufficient to meet the stringent water quality requirements given in the European Bathing Water Directive (guide value: 100 FC / 100 ml). A typical tailing effect can be observed, at which a further increase of disinfectant dosage does not result in a corresponding reduction of indicator organisms.
On the other hand, if the sample had been sonicated prior to the exposure to the different UV doses with a constant ultrasonic density of 80 W/L for 5 seconds, the desired disinfection level could be obtained quite easily: Only 10 seconds of subsequent UV irradiation are sufficient to lower the concentration of fecal coliforms by 4.5 log orders of magnitude, i.e. an improvement of disinfection efficiency by 1.3 log. Therefore, a trend in energy consumption is clearly visible: Whereas 5 seconds of ultrasonic pre-treatment and 10 seconds of UV disinfection consume 900 Ws/L to reduce fecal coliforms to a level beneath the critical concentration of 100FC/100ml, an exclusive UV irradiation of as much as 30 seconds is not capable of achieving this goal - and energy consumption was two third higher.

CONCLUSION

At low ultrasonic doses waste water sample's physical composition is changed markedly as agglomerates are declumped and subsequent disinfection by other methods like UV is facilitated. In that regard ultrasound is very useful as pre-treatment to conventional disinfection methods like chlorination or UV irradiation.

Ultrasound reactors are very small units that easily can be installed at any place on a treatment plant. In that quality ultrasound can replace sand filters that usually serve as step to remove suspended solids prior to disinfection. Sand filters are large constructions that require considerable investment and operation costs.

There is scientific and economic potential in the development of combined disinfection processes. We will carry on work on a combination of ultrasound/UV and also on ultrasound/chlorination to improve the sustainability and economy of the processes.

In order to definitely damage microbial cell walls higher ultrasound energy input is necessary. Ultrasound as an exclusive disinfection method will only be appropriate if new full scale reactors show significantly better efficiency than lab scale equipment. At present, cost implications for full scale processes cannot be properly assessed yet. However, with regard to our experience in the rapidly advancing process of ultrasonic bio-mass disintegration for intensified anaerobic sludge digestion we are optimistic to have available also sustainable full scale ultrasonic disinfection equipment soon.

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