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Application of hydrodynamic cavitation to improve the biodegradability of mature landfill leachate

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ABSTRACT

In this study, the application of hydrodynamic cavitation to improve the biodegradability of mature landfill leachate was investigated. Three configurations of cavitation device were examined and operational parameters of the process were selected. The study indicated that the orifice plate with a 3/10 mm diameter conical concentric hole, characterized by the cavitation number of 0.033, is a reasonable choice to ensure the enhanced biodegradability of mature leachate. Using such a configuration and maintaining 30 recirculation passes through the cavitation zone at inlet pressure of 7 bar, the highest increase of biodegradability index (BI) of approximately 22% occurred, i.e., from the value of 0.046 to 0.056. The FT-IR/PAS analysis confirmed a degradation of refractory compounds that typically prevail in mature leachate.

An evaluation of energy efficiency was made in terms of the actual consumed energy measured by using the Kyoritsu KEW6310 Power Quality Tester. A cavitational yield of 9.8 mg COD kJ^{-1} was obtained for the optimum configuration and 30 recirculation passes. Regarding energy efficiency, the application of 10 cavitation cycles appeared to be the most profitable. This was due to an almost threefold higher cavitational yield of 27.5 mg COD kJ^{-1}. However, the preferable option should be selected by considering a satisfactory effect in the biodegradability enhancement.

1. Introduction

Landfill leachate is a highly contaminated liquid created by the degradation of disposed waste, in combination with rainwater percolating through the refuse layers. It varies hugely with regard to amount and composition, significantly depending on numerous factors. The major determinants involve landfill technology, morphology and the type of waste gathered, compaction of refuse layers, seasonal weather variation, hydrogeology, site operations and management, as well as landfill age with the corresponding refuse decomposition stage [1,2]. According to the latter, three types of leachate have been distinguished: young, intermediate and mature. Each of these is different in composition and biodegradability.

With an increase in landfill age, there is a change in the main contribution of the organic compounds due to the degradation of volatile fatty acids that typically prevail in leachate, generated in less stabilized items. Thus, for the mature ones, the more stable refractory compounds with high molecular weights, such as humic and fulvic substances, tend to prevail. In this case, the leachate biodegradability significantly decreases [3]. Generally, mature leachate is characterized by a moderately high strength of COD (<4000 mg/L). Furthermore, it has a concentration of ammonium nitrogen that exceeds 400 mg/L, with extremely high values of 3000–5000 mg/L [4,5]. The BOD_5/COD ratio, considered to be a measure of biodegradability and known as biodegradability index (BI) [6], usually reaches the level below 0.1 [5]. Some researchers also suggest that the complexity of components, as well as the molecular size of the dissolved organic matter, increase according to landfill age. Thus, the mature leachate has a wider range of molecular weight with a high molecular weight fraction [7,8]. According to Huo et al. [8], the increment in the landfill age favors aromatic polycondensation and increases the level of conjugated chromophores, as well as the degree of humification of dissolved organic matter. In mature leachate, these scientists found a 44% concentration of humic acids, approximately 51% content of fulvic acids and 7% hydrophilic fractions of dissolved organic matter. At the same time, the contents of the young leachate were reported as follows: 0.4%, 23.6% and 76%.

Recently, the presence of humic substances in leachate has gained special attention [9]. Humic substances are natural organic

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matter made up of complex structures of polymerized organic acids, carboxylic acids and carbohydrates with molecular masses, ranging from several hundreds to tens of thousands [10,11]. They represent the non-biodegradable fraction of COD and show recalcitrant properties. Due to their structural complexity, humic substances affect the behavior of some pollutants in natural environments, for example trace metal speciation and toxicity [7]. Zhao et al. [9] reported that such substances diminish the effect of UV radiation due to UV light absorption. At present, there are several methods that are used to remove humic substances. These include coagulation–flocculation, electro-coagulation, oxidation and membrane technology [12–15]. However, none of these are considered to be commercially profitable due to their unrealistically high costs [16].

Generally, the unique characteristics of mature landfill leachate demand individual selection of various – frequently combined – biological and physicochemical pre- or post-treatments [1,17,18]. Among the physicochemical methods, advanced oxidation processes (AOPs) have recently been revealed as an effective technology in improving the biodegradability of leachate [2,4,19]. According to Vilar et al. [20,21], favorable results can be achieved by using solar photo-Fenton oxidation. Likewise, de Morais and Zamora [22] noted that the ultraviolet light/hydrogen peroxide and photo-Fenton pretreatment lasting 60 min was an efficient method to enhance the BOD_5/COD value from 0.13 to circa 0.4. These results were consistent with Bila et al.'s study [23] which involved the ozonation of leachate followed by a biological process. The researchers reported the increment in BOD_5/COD value from 0.05 to approximately 0.3. They noted that, even though the BOD_5/COD ratio was adequate for biological treatment, the process did not have a good performance. This was most likely due to the high toxicity associated with the high ammonia concentration.

Among many investigated AOPs, cavitation has been found to effectively destruct complex organic chemicals. In recent decades, increasing attention has been devoted to investigating this phenomenon as a tool of disinfection [24–28], cell disruption [29,30] and degradation of various organic compounds, e.g., pharmaceutical residues [31,32], phenols [33], pesticides [34], insecticides [35] and textile dyes [36,37]. However, most studies mainly addressed the process with regard to the synthetic wastewater containing only specific pollutants. Moreover, it is generally accepted that sole cavitation cannot be recognized as an efficient and cost-effective technique for wastewater treatment [38]. Thus, this phenomenon has often been studied in conjunction with other AOPs, i.e., processes incorporating Fenton reagent, hydrogen peroxide or carbon tetrachloride [32,39–42]. Interestingly, different chemical and physical mechanisms of pollutant degradation via cavitation have been proposed: thermal decomposition, shockwaves, shear forces, pressure gradient and the reaction of $^{\cdot}OH$ radicals with the pollutant [6,26].

With regard to the application of the cavitation phenomenon, the focus of previous studies has rarely been on biodegradability enhancement. Until now, the subject area has only been studied by Padoley et al. [6], focusing on pretreatment of distillery wastewater with the use of hydrodynamic cavitation, and by Sangave and Pandit [43], who employed ultrasounds for the same purpose. Other reports have not been found. It is particularly worthwhile to investigate the practical aspects of the phenomenon applied to enhance the biodegradability of mature landfill leachate rich in recalcitrant organic compounds (i.e., humic substances). This would allow to evaluate the possibility of subsequently using the biological treatment methods.

The present study examined the advisability of the application of hydrodynamic cavitation as a pretreatment technique for improving the biodegradability of mature landfill leachate. The effect of the constriction geometry on the cavitational results was investigated using three configurations of the cavitation device. The operational parameters were selected and discussed. The results of the study were evaluated in terms of leachate biodegradability enhancement, as well as cavitational yields. The evaluation of energy efficiency was made on the basis of measuring the actual energy consumed.

2. Materials and methods

2.1. Materials

Leachate was sourced from the Rokitno (Lublin, Poland) municipal solid waste landfill of over 15 years of age. The leachate was considered as the mature one. It was sampled eightfold, with an average collected sample of 90 L, taken from a storage tank and transported immediately (within one hour) to the laboratory using plastic containers. The content analysis was carried out upon delivery. The leachate composition is presented in Table 1 and discussed in Section 3.1.

2.2. Experimental set-up

The laboratory closed-loop installation consisted of a cavitation reactor – connected via pipes to the circulation tank – and a centrifugal pump (maximum operating pressure 16 bar, 1000–3000 revolutions per minute, power rating 2.2 kW), which generated pressure in the system (Fig. 1). The reactor was composed of a cavitation inducer (replaceable orifice plate) housed by two flanges bolted together. It also had a transparent organic glass tube (of methyl polymethacrylate), allowing the observation of the cavitation phenomenon. The experimental set-up was equipped with control valves and a measuring system consisting of Keller PR-33X piezoelectric pressure gauges with a 1 mbar resolution. These were connected to a digital data measurement/acquisition

Table 1
The characteristics of leachate samples.

Parameter	Unit	Average value ± standard deviation	Minimum	Maximum
Total chemical oxygen demand (COD)	mg L^{-1}	6051 ± 71	5498	6530
Biochemical oxygen demand (BOD_5)	mg L^{-1}	277 ± 89	126	428
BOD_5/COD	–	0.046 ± 0.014	0.022	0.069
Total organic carbon (TOC)	mg L^{-1}	1792 ± 158	1657	1937
Dissolved organic carbon (DOC)	mg L^{-1}	1594 ± 75	1517	1666
pH	–	8.08 ± 0.2	8.02	8.18
Alkalinity	mg L^{-1}	16,094 ± 232	15,500	16,750
Volatile fatty acids (VFA)	mg L^{-1}	1164 ± 28	1066	1348
Total solids (TS)	g kg^{-1}	15.5 ± 0.2	14.9	16.2
Volatile solids (VS)	g kg^{-1}	2.8 ± 0.2	1.5	3.4
Ammonium nitrogen (N-NH_4^+)	mg L^{-1}	2069 ± 815	1390	2973
Ortho-phosphate phosphorus (P-PO_4^{3-})	mg L^{-1}	26 ± 15.9	6.2	39.2