

城市污水再生处理过程中病原性原虫的去除特性

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摘要: 通过定期监测北京市某城市污水再生处理过程各单元出水中的隐孢子虫和贾第鞭毛虫(两虫)浓度, 系统考察了污水再生处理系统对两虫的去除特性. 结果表明, 原污水、初沉池出水、二沉池出水、絮凝沉淀池出水和砂滤池出水中隐孢子虫的平均检出量分别为 238、179、6、1、0.3 个 $\cdot\text{L}^{-1}$, 贾第鞭毛虫的平均检出量分别为 1 568、1 048、22、4、0.6 个 $\cdot\text{L}^{-1}$. 污水再生处理系统对隐孢子虫和贾第鞭毛虫的总去除率分别为 2.98 log(99.895%) 和 3.46 log(99.965%). 一级处理工艺对污水中两虫的去除效果并不理想, 去除率分别只有 0.13 log 和 0.18 log. 二级生物处理对两虫的去除贡献最大, 去除率分别达 1.50 log 和 1.67 log. 污水深度处理工艺(絮凝-沉淀-砂滤)能有效提高两虫的去除效果. 污水厂进水中的两虫检出量随季节变化, 雨季较低, 旱季较高.

关键词: 隐孢子虫; 贾第鞭毛虫; 病原性原虫; 污水再生利用

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Removal Characteristic of Pathogenic Protozoan in Wastewater Treatment and Reclamation Process

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Abstract: The concentration of pathogenic protozoan (*Cryptosporidium* and *Giardia*) in water samples of different units in a full-scale wastewater treatment plant in Beijing was investigated periodically. The average concentrations of *Cryptosporidium* detected in untreated wastewater, primary sedimentation, secondary sedimentation, flocculation-sedimentation and sand-filtration effluent were 238, 179, 6, 1, 0.3 oocysts/L respectively, and the average concentrations of *Giardia* were 1 568, 1 048, 22, 4, 0.6 cysts/L respectively. The total removal efficiencies of *Cryptosporidium* and *Giardia* in this treatment process were 2.98 and 3.46 log respectively. Very little protozoan in wastewater could be removed by preliminary treatment process, the removal efficiencies were only 0.13 and 0.18 log respectively. Biological treatment unit had the highest removal efficiency, up to 1.50 and 1.67 log respectively. Advanced treatment process could enhance the removal of the protozoan effectively. The results also showed that the pollution level of pathogenic protozoan in the influent of wastewater treatment and reclamation plant was various according to the climate, high in dry seasons and low in rainy season.

Key words: *Cryptosporidium*; *Giardia*; pathogenic protozoan; wastewater reuse

隐孢子虫(*Cryptosporidium*)和贾第鞭毛虫(*Giardia*)(以下简称“两虫”)是 2 种病原性原生动物, 人和动物摄入含有隐孢子虫卵囊(oocyst)和贾第鞭毛虫孢囊(cyst)的水或食物后会感染隐孢子虫病(*Cryptosporidiosis*)和贾第鞭毛虫病(*Giardiasis*). 与其他水媒疾病相比, 这 2 种病的发病率较高, 并且目前国际上尚无有效的治疗方法.

根据报道, 污水中隐孢子虫和贾第鞭毛虫的浓度很高^[1,2], 而再生水中的隐孢子虫和贾第鞭毛虫可能通过水循环污染饮用水源, 由于隐孢子虫卵囊和贾第鞭毛虫孢囊的抗性较强, 在自然界中广泛存在, 并且它们的个体非常微小, 絮凝、澄清、过滤工艺难以将其完全去除. 因此, 越来越多的研究者开始关注两虫在污水再生处理系统中的去除特性.

本研究通过定期监测北京市某城市污水再生处理过程各单元出水中的隐孢子虫和贾第鞭毛虫浓

度, 系统考察了污水再生处理系统对两虫的去除特性.

1 材料与方法

1.1 水样

试验采用 5 种水样, 分别为北京市某污水再生处理过程各工艺环节出水, 包括进水(即原污水)、初沉池出水、二沉池出水、絮凝沉淀池出水和砂滤池出水. 该污水厂的二级处理工艺采用传统活性污泥法, 二沉池出水经絮凝-沉淀-砂滤处理后成为再生水出厂, 分别用于厂区内绿化、冲洗、地表水补给等. 于 2005 年 8

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月~2006年8月定期取样进行测定.水样取回后置于暗处4℃保存,所有水质指标在24 h内测定.

1.2 试剂和材料

洗脱剂:1g Laureth-12(美国 PALL 公司生产),10 mL 1 mol/L Tris, 2 mL 0.5 mol/L EDTA, 0.15 mL Antifoam A(德国 Sigma 公司生产),加纯水至 1 L 配制而成.配制当天使用.

试剂盒:免疫磁珠分离试剂盒采用挪威 DYNAL 公司生产的 Biotech ASA,免疫荧光染色试剂盒采用澳大利亚 BTF 公司生产的 EasyStain.

滤膜:美国 Millipore 公司生产,硝酸纤维素滤膜,φ47 mm,孔径 1.2 μm.

1.3 试验方法

两虫测定方法采用本研究前期工作建立的污水再生水中病原性原虫检测方法^[3].

2 结果与讨论

2.1 污水再生处理系统中病原性原虫的污染现状

2.1.1 浓度水平

根据文献报道,不仅污水中存在高浓度的隐孢子虫卵囊和贾第鞭毛虫孢囊,经处理后的污水也是水环境中两虫的主要污染源,其受纳水域中的两虫检出量较高,存在显著的健康风险^[4~8].本研究考察了北京市某污水再生处理系统各工艺单元中的两虫存在水平,如图 1 所示.

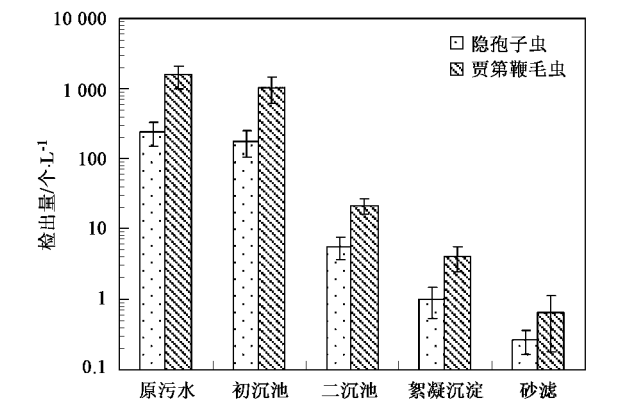


图 1 各工艺单元水样中两虫的检出量

Fig.1 Concentration of *Cryptosporidium* and *Giardia* in water samples from different units

由图 1 可知,该污水厂进水中隐孢子虫和贾第鞭毛虫浓度较高,随着处理工艺的进行两虫浓度逐渐降低.虽然二级生物处理和深度处理工艺能够将再生水中的两虫浓度降到非常低的水平,但各单元的出水中均有两虫检出,其致病风险仍然存在.

本研究中测得的污水中含有隐孢子虫 238 个·L⁻¹(平均),贾第鞭毛虫 1 568 个·L⁻¹(平均),与 Caccio 等^[9]和 Farias 等^[10]的检测结果相似.由于污水来源和检测方法的差异,其他研究者报道的污水中两虫检出量则存在一定的差异^[11~13],但基本在同一数量级,即隐孢子虫几十至几百个·L⁻¹,贾第鞭毛虫几百至几千个·L⁻¹^[14].

经一级和二级处理后,污水厂的水样中隐孢子虫的含量分别为 179 个·L⁻¹和 6 个·L⁻¹,贾第鞭毛虫的含量分别为 1 048 个·L⁻¹和 22 个·L⁻¹,明显高于曾惠芳等^[15]对深圳市污水处理厂和 Medema 等^[8]对荷兰某污水处理厂的水样检测结果.其中,二沉池出水的隐孢子虫检出量与以色列^[13]、美国^[1]和英国^[16]的污水处理厂水质检测结果非常类似,但低于宗祖胜等^[17]、Bonadonna 等^[18]的报道值.

该厂经絮凝-沉淀-砂滤后的出水,即再生水中隐孢子虫和贾第鞭毛虫的阳性率分别为 41% 和 82%,检出量分别为 0.3 个·L⁻¹和 0.6 个·L⁻¹,与 Harwood 等^[14]、Gennaccaro 等^[19]和 Ryu 等^[20]报道的再生水检测数据吻合较好.但该检出浓度明显高于世界各国对于两虫浓度的饮用水标准^[21~25].

如图 1 所示,污水再生处理系统各单元的水样中贾第鞭毛虫的浓度始终高于隐孢子虫,并且两者的检出量的变化趋势非常相似.定量考察污水再生处理全过程和各工艺环节中两虫检出量之间的相关性,结果如图 2 所示.可以看出,隐孢子虫卵囊和贾第鞭毛虫孢囊的浓度间呈现出较好的线性相关关系,贾第鞭毛虫的检出量大约是隐孢子虫的 6 倍.在

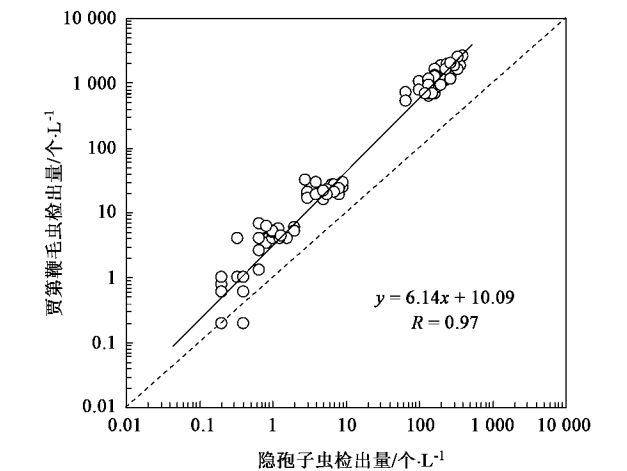


图 2 污水再生处理过程中隐孢子虫与贾第鞭毛虫检出量的相关性

Fig.2 Relationship between concentration of *Cryptosporidium* and *Giardia* in wastewater treatment and reclamation process

其他污水厂水质研究的试验中也发现贾第鞭毛虫的检出量高于隐孢子虫的现象^[8,26]。

2.1.2 季节变化

LeChevallier等^[27]根据美国6个主要水域的600多个水源水样品的分析结果认为,隐孢子虫卵囊在水源水中的存在水平与季节相关,秋季和春季时浓度较高。Aboytes等^[28]对美国14个州的82个地表水处理厂进行取样测定后发现,水源水中两虫浓度的季节性差异导致出厂水中的检出量也随季节变化^[29]。有研究者认为,这一现象是由于不同季节的降水量差异造成的^[30]。较多研究也表明,地表水中的两虫浓度基本呈现雨季高,旱季低的变化规律^[30~33]。于是,本研究考察污水厂进出水及各单元水样中两虫检出量随时间变化的关系,结果如图3和图4所示。

可以看出,该污水厂的进水和初沉池出水中两虫的检出量呈现出一定的随季节变化的趋势。整个检测过程从夏季开始,经过秋、冬两季,持续到第2年春、夏季。北京市的基本气候状况为,夏秋季降雨量较大,冬季和春季则相对干燥。两虫的检出量在雨季较低,随着降水量的减少而不断上升。这与Gibson等^[34]对城市污水的检测结果是—致的,但与上述地表水检测结果则正好相反。这是因为本研究和Gibson等研究的对象均为雨污合流系统收集的城市污水。在雨季,由于雨水的冲刷作用将更多的两虫带入地表水中导致其浓度升高,但由于污水中隐孢子虫和贾第鞭毛虫的浓度很高,雨水只能起到稀释所用,并且降雨量越大,稀释作用越强,则检出浓度也越低。因此,初步认为,对于雨污合流的城市污水收集系统,在旱季时污水中的两虫负荷较高。

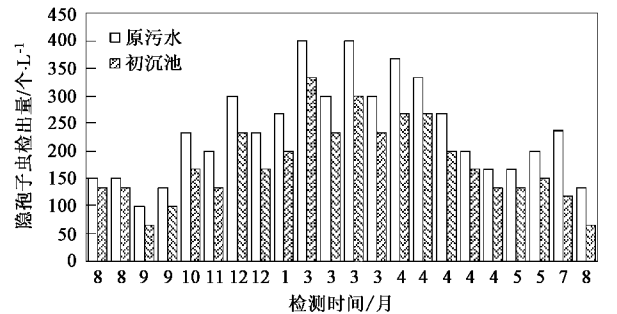


图3 污水厂污水和初沉池出水中隐孢子虫的检出量
Fig.3 Concentration of *Cryptosporidium* in water samples from influent and primary clarifier

2.2 污水再生处理过程各单元对病原性原虫的去除效果

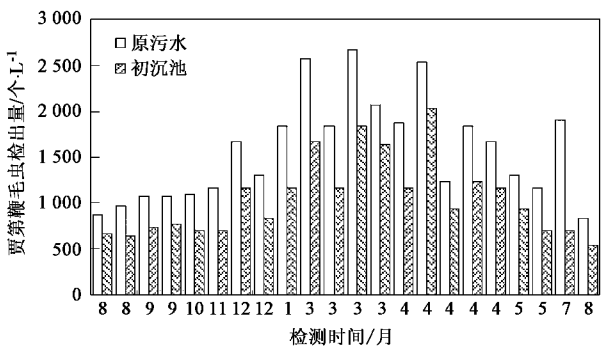


图4 污水厂污水和初沉池出水中贾第鞭毛虫的检出量
Fig.4 Concentration of *Giardia* in water samples from influent and primary clarifier

根据污水厂各工艺单元水样中隐孢子虫和贾第鞭毛虫的检出量分别计算不同处理工艺对两虫的累计去除率和去除率,如图5和图6所示。可以看出,经过二级生物处理后隐孢子虫卵囊和贾第鞭毛虫孢囊的去除率分别达到1.62 log和1.85 log。其中隐孢子虫的去除率与相关的研究结果基本一致,一般在1~2 log的范围内^[17,33],但低于渥太华污水处理厂的水质检测数据^[35]。

增加了絮凝-沉淀-砂滤的处理工艺后,该系统对隐孢子虫和贾第鞭毛虫的去除率分别上升到2.98 log和3.46 log。可见,污水深度处理工艺能够显著提高处理系统去除两虫的能力,对保障再生水的两虫安全性起到关键作用。该厂整个污水再生处理过程对两虫的去除率显著高于Caccio等^[9]对于意大利4个污水再生处理厂的检测结果。

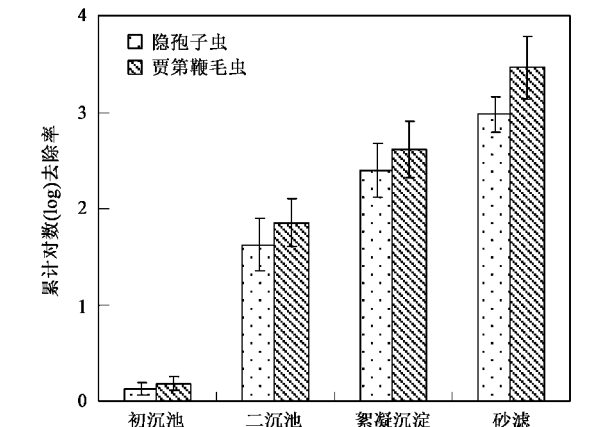


图5 污水厂各工艺单元对两虫的累计对数去除率
Fig.5 Accumulative removal efficiency of *Cryptosporidium* and *Giardia* in wastewater treatment process

如图5和图6所示,曝气沉砂-初级沉淀的一级处理工艺对污水中隐孢子虫和贾第鞭毛虫的处理效

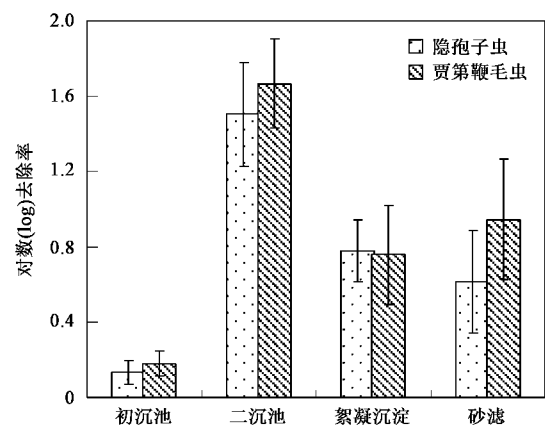


图 6 污水厂各工艺单元对两虫的对数去除率

Fig.6 Removal efficiency of *Cryptosporidium* and *Giardia* in wastewater treatment process

果并不理想,去除率分别只有 0.13 log 和 0.18 log. 其中,隐孢子虫去除率与 Payment 等^[19]对加拿大蒙特利尔某城市污水处理厂的水质检测结果接近.但与其他相关报道相比,该污水厂的初级处理工艺对两虫的去除率偏低^[9,36,37]. Whitmore 等^[38]认为,初级处理的效果不好,主要是因为与传统沉淀池设计的自由沉降速率相比,卵囊和孢囊的沉降速度要低很多.因此,沉淀等预处理工艺不能很好地将两虫从水体中分离出去.

污水二级生物处理在有效降低化学污染物浓度的同时,对两虫去除率的贡献也最大.该污水厂活性

污泥处理单元能够去除 1.50 log 的隐孢子虫卵囊和 1.67 log 的贾第鞭毛虫孢囊. Rose 等^[36,37]认为,采用活性污泥法处理污水,经过沉淀后可以去除 1.10 log 的卵囊,低于本研究的结果.但 Suwa 等^[39]对日本污水厂的水质研究表明,当污泥絮体沉降效果较好时,活性污泥法对隐孢子虫的去除率可以达到 2 log. 活性污泥法之所以能够有效去除两虫,是由于两虫黏附在污泥絮体上,通过二沉池中的沉降作用很容易被去除^[17].

由于二沉池出水中的两虫浓度已经较低,增加了絮凝沉淀和砂滤等深度处理工艺进一步去除两虫的难度.但该污水厂的絮凝沉淀池和砂滤装置对隐孢子虫的去除率仍达到 0.78 log 和 0.61 log,对贾第鞭毛虫的去除率达到 0.76 log 和 0.95 log. 这一结果与相关文献报道接近^[39,40].

定量考察各单元处理后的出水水质与原污水的相关关系,结果如图 7 所示.只有初沉池出水中的两虫浓度与污水具有较好的正相关性,线性相关系数在 0.9 以上,这可能与初级处理只经过简单的物理截留和沉降作用有关.二级处理和深度处理过程中隐孢子虫卵囊和贾第鞭毛虫孢囊的检出量与其在进水中的存在水平相关性不高.这说明,再生水的水质主要由处理系统的运行和维护状况决定,同一污水再生处理系统中进水负荷较高并不意味着出水水质就较差^[41].

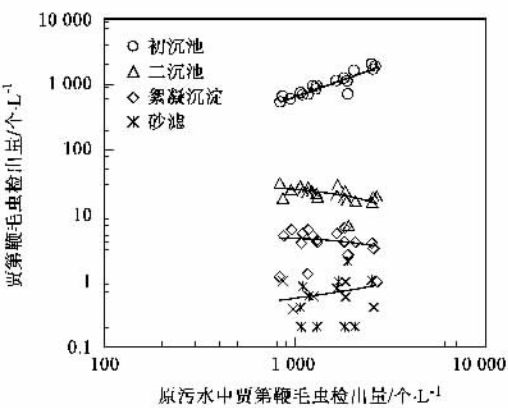
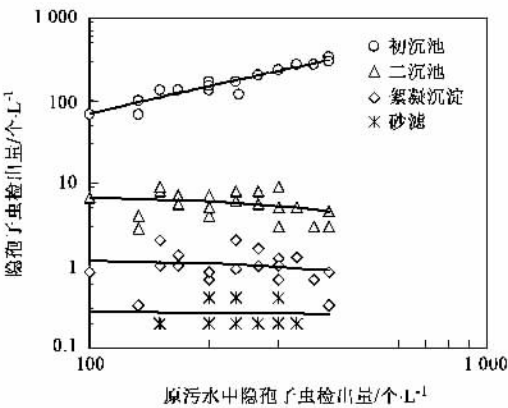


图 7 其他工艺单元出水中的两虫检出量与污水的相关性

Fig.7 Relationship between concentration of *Cryptosporidium* and *Giardia* in water samples from influent and other units of wastewater treatment process

3 结论

(1) 污水厂进水中隐孢子虫和贾第鞭毛虫浓度较高,随着处理工艺的进行两虫浓度逐渐降低,但再

生水中仍有两虫检出.

(2) 由于采用了雨污合流的污水收集系统,污水厂进水中的两虫检出量随季节变化,雨季较低,旱季较高.

(3) 本研究的污水再生处理系统对隐孢子虫和贾第鞭毛虫的去除率分别为 $2.98 \log(99.895\%)$ 和 $3.46 \log(99.965\%)$ 。一级处理工艺对污水中两虫的去除效果并不理想,去除率分别只有 $0.13 \log$ 和 $0.18 \log$ 。二级生物处理对两虫的去除贡献最大,去除率分别达 $1.50 \log$ 和 $1.67 \log$ 。污水深度处理工艺(絮凝-沉淀-砂滤)能有效提高两虫的去除效果。

(4) 再生水的水质主要由处理系统的运行和维护状况决定,进水两虫负荷较高时出水水质不一定较差。

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