论文中英文摘要

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论文题目：废水生物处理反应器中微生物聚集体表面特性的研究

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中　文　摘　要

生物处理是水污染控制的主要技术手段，而废水处理反应器中微生物聚集体的表面特性决定着反应器运行的稳定性、处理效率和出水水质，在废水的生物处理中起着重要作用。微生物在降解废水基质的同时所产生的一种大分子物质—胞外聚合物(Extracellular polymeric substances, EPS)，覆盖在微生物的表面，及填充在各种微生物聚集体内部空隙中，维持着各种微生物聚集体的结构和功能的完整性，是决定其表面性质的关键物质。对微生物聚集体表面特性的研究集中在其产生的 EPS 上。本论文系统地研究了废水处理反应器中微生物聚集体的表面特性，探索了在不同培养条件下 EPS 的形成规律，并深入探讨了 EPS 成分和含量与聚集体结构功能之间的内在关系。主要研究内容和研究结果如下：

1．通过对光合细菌 EPS 提取方法的比较研究，优化了光合细菌 EPS 的提取步骤，提出一种判别细胞破坏程度的新方法。研究结果表明：EDTA 法提取效率高，对细胞的破坏少，适用于从光合细菌中提取 EPS，适宜的提取时间和提取剂用量分别为 1-3 小时和 2.8 g/g 细胞干重；提取方法、提取时间、提取剂用量都可以影响 EPS 的含量和成分；并提出利用紫外可见光谱来评价提取过程中细胞的破坏程度，方法快速、简便。

2．建立了一种快速分析废水处理反应器中微生物聚集体 EPS 吸附特性的方法，并研究了 EPS 和小分子染料之间的相互作用。这种方法是基于测定染料和染料-EPS 的复合物之间的吸收光谱的差别，进而通过吸附模型计算出 EPS 的结合常数和最大结合数。研究结果表明 EPS 具有很强的结合小分子染料的能力，在 pH 11.0 下，从好氧和厌氧污泥中提取的 EPS 的最大结合数分别为 1.86 mmol/g EPS 和 0.56 mmol/g EPS；EPS 与小分子染料之间是通过静电相互作用结合在一起的。

3．通过三维荧光光谱这一快速、高灵敏、高选择性的无损分析方法，表征了好氧和厌氧污泥 EPS 的特性。结果表明：在两种 EPS 的三维荧光光谱上出现了三个荧光峰，其中两个峰

是由蛋白类物质产生的，第三个峰是由腐殖质类物质产生的；两种 EPS 的三维荧光光谱参数，如峰位置、峰强度、不同峰强度比都有所不同，说明了两者在成分和结构上的差别。

4．采用三维荧光光谱和 zeta 电势两种快速灵敏的无损分析方法，探索了 EPS 和金属的不同作用机理。研究发现 EPS 和 Ca^{2+}主要是通过静电相互作用结合在一起的，而 EPS 和 Hg^{2+}或 Cu^{2+}却是通过配位共价键结合在一起。

5．以两株产氢光合细菌为对象，表征了细胞及其 EPS 表面的红外光谱特性及化学成分。作为一个简单、快速、直接的分析手段，红外光谱可以用来快速测定废水处理反应器中微生物聚集体表面及其 EPS 中主要物质的相对含量；红外光谱测定结果和传统的化学比色法测定结果一致。

6．系统地研究了微生物聚集体的稳定性，阐明了 EPS 与其稳定性的关系：基于 Langmuir 吸附理论，考虑温度的影响，修正了吸附－解吸污泥稳定性模型，拓宽了该模型使用范围；基于化学平衡的概念，建立了一个新的具有普适性的污泥稳定性模型，该模型和实验数据符合的很好，而且适用范围更广；EPS 显著影响污泥稳定性，一般易提取 EPS 部分的相对含量越小，污泥稳定性越好；根据粒子在不同剪切作用下的可扩散能力，建立了污泥絮体结构多层模型：外部区域为扩散层，内部区域为稳定层。

7．探索了不同生长因子对光合细菌 EPS 产生的影响，揭示了 EPS 成分和含量与细菌表面特性的关系。EPS 的成分和含量与培养时间、底物类型、NaCl 浓度、碳源和氮源浓度有显著关系，而 $CaCl_2$ 却对 EPS 含量没有显著的影响；在有毒化学物质存在情况下，EPS 含量会显著增加，然而当有毒物质浓度超过一个阈值后，不会显著增加细菌的 EPS 含量；EPS 显著影响光合细菌的表面物化特性，EPS 含量和蛋白/多糖越高，细菌接触角相对就越小，表面能越大。

8．研究了在厌氧酸化产氢过程中结合型 EPS 和溶解型 EPS 的形成规律。部分 EPS 可以作为碳源和氮源供微生物生长和代谢，而惰性 EPS 会残留在细菌表面；溶解型 EPS 含量和产氢过程中的比产氢速率、比底物降解速率、比液相产物形成速率有很好的相关性，而结合型 EPS 含量与这些参数之间没有显著的相关性，但它们的含量都显著影响污泥的表面特性。

关键词：　废水生物处理；胞外聚合物；微生物聚集体；表面特性

Surface characteristics of microbial aggregates in wastewater treatment bioreactors

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ABSTRACT

Biological treatment is one of the most widely used techniques in wastewater treatment fields. The surface characteristics of microbial aggregates in bioreactors play crucial roles in biological wastewater treatments by significantly influencing the stability, treatment efficiency and effluent quality of systems. Extracellular polymeric substances (EPS) are produced by the microorganisms in bioreactors when organic materials present in wastewater are consumed. EPS are a major component of microbial aggregates for keeping the cells together in a three-dimensional matrix. They are a key element governing the microbial aggregate surface characteristics. Thus, studies on the surface characteristics of microbial aggregates should be focused on their EPS. However, to date, as EPS are very complex substances, their characteristics and roles in biological wastewater treatment have not been well documented. In this dissertation, some innovative analytical methods and techniques were employed for characterizing the EPS from various origins. The production of EPS under various cultivation conditions and the roles of EPS in microbial aggregates were also explored. The main contributions to the current understanding of this topic are described below:

1. Various EPS extraction methods - EDTA, NaOH, H_2SO_4, heating and high-rate centrifugation - were studied by extracting EPS from photosynthetic bacteria and the EDTA method was found to be the most effective means among the five extraction methods. The composition of extracted EPS greatly depended on the extraction method, extraction time and the dosage of extractant. The UV-Visible spectrometry, an easy and rapid technique, could be used to monitor the cell lysis during EPS extraction from photosynthetic bacteria.

2. A simple and rapid method for the determination of EPS adsorption characteristics was developed from the finding that EPS molecules can bind dye to produce a dye-EPS complex, this causing a shift in visible spectra of the dye solution. From the Langmuir adsorption isotherm, the maximum adsorption capacity of EPS could be calculated. Results show that EPS had a high adsorption capability.

3. The 3-dimensional excitation-emission matrix (EEM) fluorescence spectroscopy, which is a rapid, sensitive and selective analytical method, was applied to characterize the EPS extracted from both aerobic and anaerobic sludge. Three fluorescence peaks were observed in the EPS fluorescence

spectra, which were identified at (excitation/emission) 225/340-350 nm, 280-285/340-350 nm and 330-340/420-430 nm. The first two peaks were attributed to the protein-like fluorophores, and the third to the humic substances-like fluorophores. The differences in the EPS fluorescence parameters, e.g., peak locations, peak intensities and ratios of various peak intensities, indicate the difference in the chemical structures of the EPS extracted from various origins. EEM spectroscopy was proven to be an effective method to characterize the EPS extracted from various origins in wastewater treatment systems.

4. The interaction mechanisms between sludge EPS and three metal ions, Ca^{2+}, Cu^{2+} and Hg^{2+} were investigated using two rapid and sensitive analytical methods, i.e., EEM spectroscopy and zeta potential measurement. Results show that Ca^{2+} had a significant effect on the zeta potential of EPS, but no effect on the EEM spectra of EPS. The fluorescence peak intensities of EPS decreased with an increase in Cu^{2+} and Hg^{2+} concentrations, while the zeta potential of EPS did not change significantly with the addition of Cu^{2+} or Hg^{2+}. These results indicate that Ca^{2+} was bound to EPS through electrostatic interaction, and that Hg^{2+} or Cu^{2+} was bound to EPS through complexing covalent bond.

5. The Fourier transform infrared (FTIR) spectra of the cells of two photosynthetic H_2-producing strains as well as their EPS were evaluated. Results show that, as an easy, rapid and direct technique, FTIR spectroscopy could be used to characterize the chemical composition of bacteria and their EPS. The ratios among the main components in the EPS obtained from the FTIR spectra were in good agreement with those obtained using a conventional quantitative chemical analysis.

6. A model describing sludge stability was established and the roles of EPS in the sludge stability were investigated. Based on the chemical equilibrium theory, a new model was established to evaluate the stability of sludge in biological wastewater treatment systems. The equilibrium mass concentration of the dispersed primary particles in the sludge solution was found to nonlinearly increase with the sludge content and shear intensity, and was well described by the model. The stability closely correlated with the chemical composition of the readily-extractable EPS. A lower fraction of the readily-extractable EPS fraction in total EPS and a lower ratio of proteins/carbohydrates were responsible for the greater stability of sludge. The total content of the EPS, however, had a slight effect on the sludge stability. A hypothesis about biological flocs with two distinct structural regions was proposed. The outer part of sludge flocs was dispersible and the inner was stable.

7. The factors affecting the production of EPS of a H_2-producing photosynthetic bacterial strain were evaluated. The chemical composition of EPS was significantly influenced by the cell growth phase, type of substrate, NaCl concentration and concentrations of carbon and nitrogen sources, while were slightly influenced by $CaCl_2$ concentration. The production of EPS increased

considerably when the bacterium was exposed to toxic substances, but as the concentration of toxic substances exceeded a threshold, it did not significantly stimulate its EPS production.

8. Finally, the formation of bound EPS and soluble EPS in an anaerobic H_2-producing process was investigated. Results confirm that some biodegradable EPS could be utilized by the H_2-producing sludge and some inert EPS remained at the cell surface. The soluble EPS were well correlated with the specific H_2 production rate, specific substrate degradation rate and specific aqueous product formation rate, while the bound EPS had no such correlations with these specific rates. However, both bound and soluble EPS were related to sludge surface characteristics.

Key words: Biological wastewater treatment; extracellular polymeric substances (EPS); microbial aggregates; surface characteristics