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Review

Pollutant removal-oriented yeast biomass production from high-organic-strength industrial wastewater: A review

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ABSTRACT

Microbial single-cell-protein (SCP) production from high-organic-strength industrial wastewaters is considered an attractive method for both wastewater purification and resource utilization. In the last two decades, pollutant removal-oriented yeast SCP production processes, i.e., yeast treatment processes, have attracted a great deal of attention from a variety of research groups worldwide. Different from conventional SCP production processes, yeast treatment processes are characterized by higher pollutant removal rates, lower production costs, highly adaptive yeast isolates from nature, no excess nutrient supplements, and are performed under non-sterile conditions. Furthermore, yeast treatment processes are similar to bacteria-dominated conventional activated sludge processes, which offer more choices for yeast SCP production and industrial wastewater treatment. This review discusses why highly adaptive yeast species isolated from nature are used in the yeast treatment process rather than commercial SCP producers. It also describes the application of yeast treatment processes for treating high-carboxyhydrate, oil-rich and high-salinity industrial wastewater, focusing primarily on high-strength biodegradable organic substances, which usually account for the major fraction of biochemical oxygen demand. Also discussed is the biodegradation of xenobiotics, such as color (including dye and pigment) and toxic substances (including phenols, chlorophenols, polycyclic aromatic hydrocarbons, etc.), present in industrial wastewater. Based on molecular information of yeast community structures and their regulation in yeast treatment systems, we also discuss how to maintain efficient yeast species in yeast biomass and how to control bacterial and mold proliferation in yeast treatment systems.

1. Introduction

Yeasts are a group of unicellular fungi widely distributed in nature, most of which belong to two separate phyla: the Ascomycota and the Basidiomycota. Yeasts have played

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important roles in the fermentation and food industries for thousands of years. Their obligatory acidophilic properties suggest that the fungi would not act as an opportunistic pathogen [1]. The protein extracted from yeast biomass, single cell protein (SCP), can replace costly conventional proteinaceous sources (e.g., soymeal and fishmeal) for animal feeds.

High-organic-strength industrial wastewaters often represent a significant loss of resources and causes serious pollution problems [2]. SCP production from these wastewaters is an attractive approach to both wastewater purification and resource utilization [3]. In most cases, the analyzed SCP composition mainly includes protein concentration, amino acid profiles, vitamins, carbohydrates, fats, and nucleic acids [4]. Since World War II, many yeast species have been used to produce SCPs from industrial wastewaters, a process that has been very important for numerous chronically malnourished people worldwide [5]. However, the conventional SCP process requires a pure yeast strain, expensive sterilization processes [6], optimized culture conditions (e.g., pH adjustment, extra nutrient supplement [N, P, Mg, Ca, Fe, Zn, Cu, Mn, and vitamins] [7], dilution rates [8]), and an air saturation of $\geq$20% dissolved oxygen (DO) by aeration [9] to achieve the maximum yeast biomass production. This results in high SCP production costs, low organic removals, and high nutrient residues that require post-treatment to control their discharge.

After the 1980s, numerous highly adaptive yeast strains for various industrial wastewaters have been isolated from a variety of sources (e.g., wastewater-contaminated soil, activated sludge) to replace commercial SCP yeast species due to their higher pollutant removal performances [10]. The pollutant removal-oriented SCP production processes, i.e., yeast treatment process, is characterized by higher pollutant removals, lower production costs, isolated yeast species, no excess nutrient supplements, and is performed under non-sterile conditions in a system similar to bacteria-dominated conventional activated sludge process (ASP) [6,11,12]. Its organic loading amounts to at least 15 $kg\cdot m^{-3}\cdot d^{-1}$ chemical oxygen demand (COD) [13], which is nearly 10 times higher than conventional ASPs, thus offering more choices for yeast SCP production and industrial wastewater treatment.

2. Yeast species used in yeast treatment process

For conventional SCP processes, higher SCP production and protein content, and more plentiful and balanced amino acids essential for animal feed tend to make the selected yeast species or strain more attractive [14]. The most popular SCP yeast species are from the genera *Candida*, *Hansenula*, *Pichia*, *Torulopsis* and *Saccharomyces* [4]. In many cases, *Candida utilis* is frequently used for biomass production from a variety of carbon sources due to its high SCP production and specific growth rate [14,15]. However, the yeast species found in industrial wastewater treatment systems represent 48 taxa belonging to 21 different genera, of which the most frequent populations are from the genera *Rhodotorula*, *Candida*, *Trichosporon*, *Pichia* and some unidentified *Ascomycetes* [16]. This suggests that those commercial SCP yeast species may not be the most suitable for yeast treatment processes. For example, *Candida langeronii* appeared superior to *C. utilis* for biomass production from hemicellulose hydrolysate since the latter cannot utilize L-arabinose and grow at 42 °C [14].

Yeast strains of differing origins have different pollutant removal potentials [17], and isolated yeast strains obtained by spontaneous selection pressure in wastewater often reduce more COD and produce more yeast biomass than conventional SCP producers [10,18]. Furthermore, specific yeast species often selectively utilize preferential carbon sources prior to other carbon sources [14], or use metabolic byproducts generated by other yeast species in mixed culture [2]. In other words, mixed yeast cultures often result in higher biomass yield and greater pollutant removal from industrial wastewater containing a variety of carbon sources [2,11]. Therefore, yeast treatment processes use highly adaptive mixed yeast isolates rather than commercial SCP producers to treat corresponding industrial wastewaters.

3. High-organic-strength wastewater treatment

Yeasts show high tolerance to low pH, high salinity, high-content organics, antibiotics, and sterilizers [19], and can metabolize various carbon substrates, including sugars (e.g., glucose, sucrose and maltose), biopolymers (e.g., starch, cellulose, hemicellulose and pectin), pentoses, methanol, alcohols, polyols, hydrocarbons, fatty acids and organic acids [7]. Industrial wastewaters are often highly acidic (pH $<$ 5) and require a pH adjustment to 6.5–7.6 to reduce pH toxicity against bacteria for ASPs or anaerobic processes [20]. Following the yeast treatment process, the pH levels of these acidic industrial wastewaters often rise to neutral [6,10,21], which reduces wastewater treatment costs and facilitates subsequent ASPs. Therefore, yeast treatment processes appear to be more suitable and cost-effective for the treatment of acidic, oily, high-salinity, ammonia- or sulfate-ridden high-organic-strength industrial wastewaters that are not suitable for direct treatment by anaerobic processes. In addition to soluble organic substances, most yeast directly assimilate ammonium ions, urea, inorganic phosphates and sulphates [7]. However, higher nitrogen removal for the yeast system compared to the bacterial system has been attributed to higher nutrient (nitrogen and phosphorous) uptake in the yeast cells compared to bacterial cells [22]. In recent years, an *in vitro* detectable polyphosphate-synthesizing activity has been characterized in extracts of the yeast *Candida humicola*, and its properties were similar to those of a range of bacterial polyphosphate kinase enzymes [23].

3.1. *High-carbohydrate wastewater*

Yeasts can metabolize various carbon substrates; however, they mainly utilize sugars (e.g., glucose, sucrose and maltose) [7]. Therefore, the concept of using yeasts to bioconvert high-carbohydrate wastewaters has long attracted the attention of SCP researchers. High-carbohydrate wastewater for SCP processes is produced widely in many food processing industries [13], e.g., starch processing wastewater [24], waste cassava starch hydrolysate [9], deproteinized whey [25], and defatted