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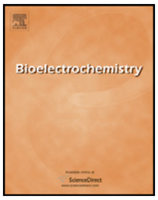

# Microbial fuel cells in saline and hypersaline environments: Advancements, challenges and future perspectives☆

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ABSTRACT

This review is aimed to report the possibility to utilize microbial fuel cells for the treatment of saline and hypersaline solutions. An introduction to the issues related with the biological treatment of saline and hypersaline wastewater is reported, discussing the limitation that characterizes classical aerobic and anaerobic digestions. The microbial fuel cell (MFC) technology, and the possibility to be applied in the presence of high salinity, is discussed before reviewing the most recent advancements in the development of MFCs operating in saline and hypersaline conditions, with their different and interesting applications. Specifically, the research performed in the last 5 years will be the main focus of this review. Finally, the future perspectives for this technology, together with the most urgent research needs, are presented.

**Contents**

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## 1. Introduction

### 1.1. Saline and hypersaline wastewaters

Saline pollution of wastewater is a critical issue to be addressed in the near future. Specifically, wastewater can be distinguished in saline, highly saline and hypersaline depending on the total dissolved inorganic salt content (TDS), being between 0 and 1%, 1 and 3.5% and over 3.5% w/v, respectively [1]. Different industries generate effluents that are characterized by a high salinity, with some examples including: the fish industry, food processing, textile, leather, and petroleum industries. The tanning process, required to obtain finished leather products, produces wastewater containing as much as 80 g $L^{-1}$ of NaCl [2]. Oilfield wastewater properties depend on the geological location, but the content of salts can reach 300 g $L^{-1}$ [3]. Additionally, seawater is utilized to flush toilets, generating saline wastewater, in coastal cities such as Hong Kong [4]. Considering the water scarcity and water insecurity that characterize approximately 80% of the global human population [5], the utilization of seawater for toilet flushing in cities located close to the seashore could represent a more sustainable future development [6]. Nowadays, saline wastewater represents around 5% of the wastewater produced globally [7]. However, the discharge into the environment of saline and hypersaline wastewater, without performing any treatment, can lead to contamination of surface and groundwater, as well as of the soil [2]. Accordingly, environmental concerns related to the increasing amount of these wastewaters have pushed the legislation of many countries to define characteristic of the water to be discharged, making the development of detailed treatment techniques of primary importance [8,9].

### 1.2. Treatment of saline and hypersaline wastewater

Aerobic biological treatment is the most utilized technique for the treatment of civil and industrial wastewaters worldwide. However, the presence of high salinity can negatively affect the efficiency of the process, since NaCl can inhibit the activity of bacterial species. The imbalance of salt concentration inside the cellular membrane of bacterial cells and the external solution causes an osmotic pressure. Thus, when bacterial cells are in solution characterized by high osmotic concentrations, they can suffer dehydration, where water that exits the cellular membrane leads to cell death (Fig. 1) [10].

Kargi and Dincer showed that increasing the salt concentration from salt-free wastewater to 5% (50 g $L^{-1}$) resulted in a 30% reduction in the Chemical Oxygen Demand (COD) removal efficiency [11]. Pernetti and Di Palma showed that salt inhibition is higher in batch mode operation (with saline influent supplied as shock-load), rather than the inhibition observed in continuous mode, where the activated sludge could acclimate to the saline medium. However, even in continuous mode, an 81% respiration inhibition was obtained when 35.5 g of NaCl over gram of volatile suspended solids were present [1]. The application of halotolerant bacteria, which are able to tolerate high salinities, is one of the best solutions to improve the performance of aerobic treatment process. Halotolerant bacteria utilize two main strategies to adapt to the presence of high salt content: the "salt in" strategy, and the "compatible solutes accumulation". In the "salt in strategy" bacterial cells are able to accumulate ions (mainly potassium) to increase the intracellular ion concentration, allowing for the balancing of the osmotic pressure [12]. In the "compatible solutes accumulation" strategy, bacterial cells can adapt to increased osmotic stress by accumulating compatible solutes. These compounds are defined as small, soluble, organic molecules that can be present inside the cellular membrane in high concentrations without affecting the normal cellular metabolism. Some examples include polyols, glycine betaine and β-glutamine [12,13] (Fig. 2).

Different reports concerning the use of halotolerant bacteria in biological processes can be found. Lefebvre et al. reported that using halophilic organisms resulted in a COD removal of 95% in the presence of 35 g $L^{-1}$ of NaCl. Under fluctuating salinity conditions, the microbial consortium was not be able to adapt to the highest salinity, and 50 g $L^{-1}$ of NaCl were the limit value to ensure the proper operation of their treating system [14]. Arulazhagan and Vasudevan isolated a halotolerant bacterial strain, which was capable of reducing 66% of COD and efficiently degraded polycyclic aromatic hydrocarbons, such as naphthalene, fluorine, and anthracene, achieving >88% degradation in the presence of 30 g $L^{-1}$ of NaCl. However, the degradation performance was highly influenced by salinity and available nutrients, with a strong decrease of the degradation in the presence of 60 g $L^{-1}$ of NaCl [15].

The anaerobic digestion of saline effluents has been investigated in a narrower range of salinity compared to the aerobic treatment, mostly due to the fact that sodium concentrations higher than 10 g $L^{-1}$ have a strong inhibiting effect on methanogenesis [2]. Ma et al. isolated an alkaliphilic halotolerant bacterium able to perform anaerobic decolorization (azo group reduction) using different electron donors, such as glucose and sucrose [16]. Lefebvre et al. studied the anaerobic digestion of tannery soak liquid in an upflow anaerobic sludge blanket showing that, after adaptation of the sludge to increasing salinity levels, a COD removal of 78% was achieved in the presence of 71 g $L^{-1}$ TDS, if the organic loading rate was maintained at low levels (0.5 kg COD $m^{-3}$ $day^{-1}$) [17]. Different studies were aimed at decreasing sodium toxicity in anaerobic digestion. Vyrides et al. reported the positive effects of 1 mM glycine-betaine in a medium containing 35 g $L^{-1}$ of NaCl to alleviate

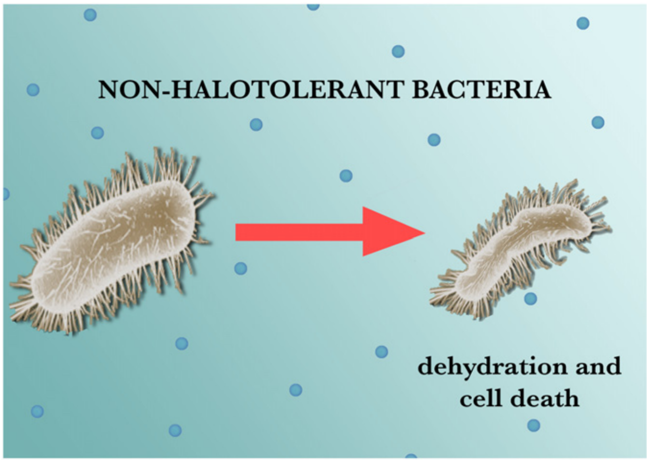

**Fig. 1.** Schematic representation of high salinity effects on non-halotolerant bacteria.

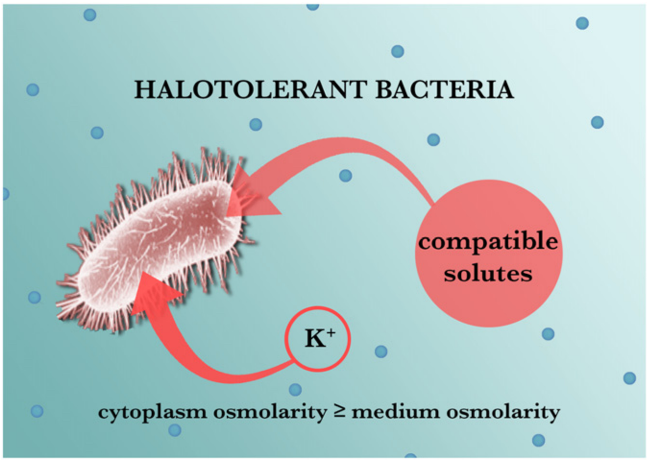

**Fig. 2.** Schematic representation of halotolerant bacteria strategies for adaptation to high salinity.