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REVIEW

Biotreatment of high-salinity wastewater: current methods and future directions

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Abstract

Saline wastewaters are usually generated by various industries, including the chemical, pharmaceutical, agricultural, and aquacultural industries. The discharge of untreated high-salinity wastewater may cause serious environmental pollution and damage the aquatic, terrestrial, and wetland ecosystems. For many countries, the treatment of saline wastewater has become an important task. Generally, saline wastewaters are treated through physical and chemical methods. However, these traditional techniques are associated with higher treatment costs and the generation of byproducts. In contrast, biotreatment techniques are environmentally friendly and inexpensive. This review highlights the sources and environmental concerns of high-salinity wastewater and illustrates the latest problems and solutions to the use of biological approaches for treating saline wastewater. Although high salinity may inhibit the effectiveness of aerobic and anaerobic biological wastewater treatment methods, such strategies as selecting salt-adapted microorganisms capable of degrading pollutants with tolerance to high salinity and optimizing operating conditions can be effective. This mini-review may serve as a reference for future efforts to treat high-salinity wastewater.

Keywords Biotechnology · High-salinity wastewater · Biological reactors · Halophilic microorganisms

Introduction

Salinity is an important parameter for wastewater treatment (Kartal et al. 2006). Wastewater is defined as "high-salinity" or brine when the inorganic salt contents range from 1 to 3.5% w/w, and seawater usually contains 3.5% w/w sodium chloride (Pernetti and Di Palma 2005). High-strength wastewater with variable salinity and nutrient loads was produced in a number of industrial processes (Jesus et al. 2017), such as aquaculture in coastal areas, the nuclear industry, agriculture and food-processing, petroleum and natural gas extraction and leather manufacturing (Calheiros et al. 2012; Lutz et al. 2013; Jesus et al. 2014; Lee et al. 2016; Zhang et al. 2019a). However, the discharge of untreated high-salinity wastewater may cause serious environmental pollution and affect the aquatic life, water potability, and agriculture (Lefebvre and Moletta 2006).

Therefore, it is necessary to use various methods and technologies to treat high salinity wastewater. Physiochemical techniques usually used to treat saline wastewater; however, they are energy-consuming with long startup time and high operating costs (Lefebvre and Moletta 2006). Nowadays, there are some documented cases where biotechnology has been used successfully for treating saline wastewater from multiple sources. However, a comprehensive assessment regarding the feasibility of using biotreatment for the treatment of high-salinity wastewater is not available. Therefore, the review aimed to (1) outline the major sources of high-salinity wastewaters and their environmental

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influences; (2) summarize the traditional treatment technologies for high-salinity wastewater; (3) emphasize the functions and mechanisms of major biotreatment technologies for high-salinity wastewater; and (4) put forward the future recommendations for biotreatment technologies for high-salinity wastewater.

Sources and environmental concerns of high-salinity wastewater

The composition and concentration of saline wastewater depend on their sources (Liang et al. 2017). There were several main sources of high-salinity wastewater: wastewater discharged during direct seawater use, aquaculture, agricultural runoff from saline-alkali lands, and industrial processes (Fig. 1).

Due to the shortage of global freshwater resources, the direct use of seawater has become a feasible solution (Voutchkov 2018). Some coastal cities, such as Hong Kong and Qingdao, use seawater for fire control, road flushing, toilet flushing and other nondirected contacts with human beings, and it is considered an important option to relieve the pressure on fresh water (Chen et al. 2012; Li et al. 2018c). High-salinity wastewater discharged from the direct use of seawater drains into the sewer affects the subsequent wastewater treatment plant (WWTP) degradation process (Liu et al. 2016). In addition, China is the world's largest producer of aquaculture products, but the high level of mariculture is associated with many environmental issues (Xiang 2007). Inorganic nitrogen, active phosphate phosphorus, organics, and salts are the main pollutants in maricultural pollution areas (Liang et al. 2018). Seawater soda industries also produce a large quantity of high-salinity wastewater. For example, high concentrations of salts (NO_3^-: 188 g/L; total dissolved solids (TDS):1.63×10^5 mg/L) wastewater from some soda ash factories discharged into Arabian Sea were reported by Jadeja and Tewari (2007). Most desalination plants use reverse osmosis (RO) to desalinate seawater and brackish water; thus, these processes inevitably produce RO concentrate. The salinity of concentrate from seawater RO (SWRO) desalination facilities was up to $6.5–8.5 \times 10^3$ mg/L (Missimer and Maliva 2018).

The accumulation of soluble salts in the soil has caused land degradation, water quality deterioration and serious problems related to agricultural development (Cassel and Sharma 2018; Fang et al. 2005). More than 20% of agricultural land is threatened by salinization globally. The salinized soils covered approximately one-tenth of the Chinese total land area, accounting for 100 Mio. ha (Li 2010). However, the area of saline-alkali land is still expanding (Wei and Zhang 2018): saline-alkali soil area increased from 401.48×10^3 in 1954 to 1097.45×10^3 ha in 2005 in the western Songnen Plain, China (Yang et al. 2010), and continued desertification and salinization of the grasslands in the source regions of the Yangtze and Yellow Rivers was observed from 1968 to 2008 (Na et al. 2013). When the saline alkali soil area was over-irrigated or rainfall occurred, it became a source of saline wastewater (Liang et al. 2017). Approximately $1.3–2 \times 10^8$ m^3 saline-alkaline farmland drainage flows into the south of Chagan Lake from the Qianguo irrigation area every year

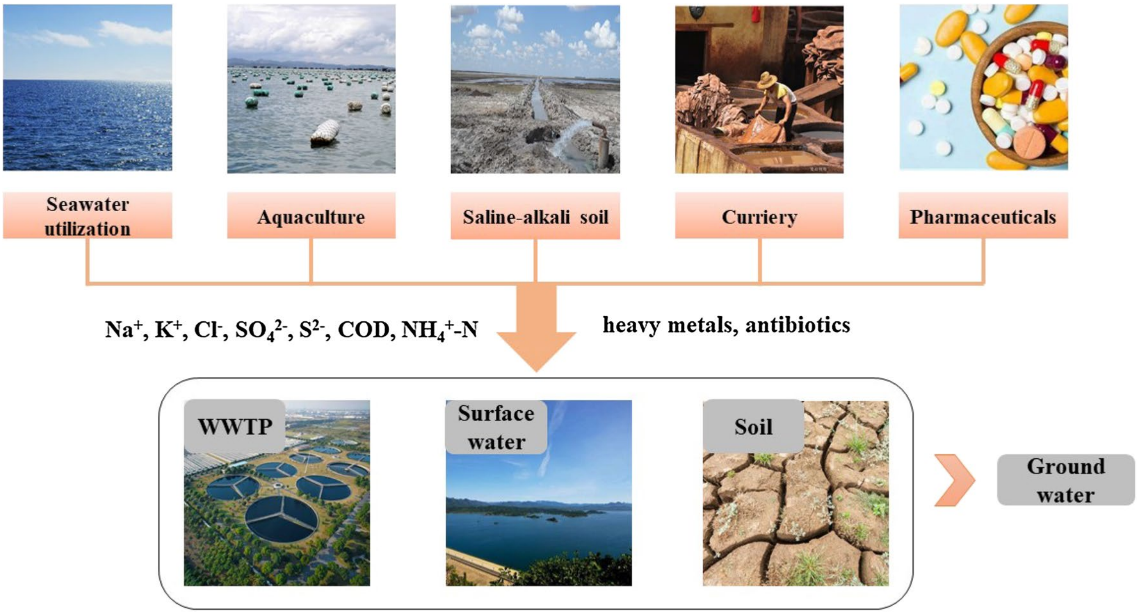

Fig. 1 Source and entry pathway of high salinity wastewater in the environment

(Yang et al. 2015). Generally, the soluble salt concentration is characterized by the conductivity (EC) value or by measuring the TDS (Liang et al. 2017). In the Aksu Oasis area of Northwest China, the TDS in irrigation water increased from 1200 to 9.01×10^3 mg/L in drainage (Hu et al. 2019). In the Arys Turkestan Canal zone (Southern Kazakhstan), the TDS value of irrigated agricultural drainage exceeds 1200 mg/L, and Na^+ and HCO_3^- are the main constituents of dissolving salts (Karimov et al. 2009). An average TDS of 1191.33 mg/L was detected in drainage water of the Fayoum watershed, Egypt (Abdel Wahed et al. 2015).

Industries such as printing, dyeing, refining, chemicals, mining, curriers, pharmaceuticals, and food processing may produce high saline wastewater. The wastewater from printing and dyeing practices had high pH, high turbidity, poor biodegradability, complex composition, and high chrominance and contained inorganic contaminants, such as chloride, heavy metals, sulfate, sulfide, and nitrogen (Xu et al. 2018). Hossain et al. (2018) reported that the TDS values of the knit dyeing and woven dyeing industries in Bangladesh were as high as 2000–3000 mg/L and 5000–6000 mg/L, respectively. In leather manufacturing, after tanning processes, approximately 40% of the chromium amount remains in the solid and liquid wastes, especially spent tanning solutions (Fabiani et al. 1996). In addition, saline wastewater is discharged during soaking, liming, deashing, pickling, chrome tanning, and finishing operations (Xiao and Roberts 2010). The TDS concentration in tanneries ranges from 65.4 to 1281.1 mg/L in Nigeria (Akan et al. 2007). In the Lokpaukwu-Ishiagu mining areas of southeastern Nigeria, it is conservatively estimated that nearly 3.3×10^4 m^3 of untreated drainage of abandoned mines, including approximately 710,000 kg of dissolved solids and 586 kg of potentially toxic metals, ran out to the Ivo River watershed each year (Ezekwe et al. 2013). Pharmaceutical wastewater carries not only chemical oxygen demand (COD), ammonia, and suspended solids but also organic and inorganic constituents (e.g., spent solvents, catalysts, and reactants) (Fent et al. 2006; Lefebvre and Moletta 2006). For example, an average TDS of 22,168 mg/L with Cl^-, PO_4^{3-}, Na^+, and K^+ as the major salts were reported in pharmaceutical wastewater of a Singapore pharmaceutical factory (producing penicillin family antibiotics) (Ng et al. 2014).

A large amount of high-salinity untreated wastewater that is discharged directly is the source of high-strength wastewater, which causes great damage to the environment. High-salinity wastewater strongly reduces soil productivity, worsens the water environment, hinders economic development and threatens food production.

Treatment technologies for high-salinity wastewater

The treatment methods and technologies of high-salinity wastewater are mainly divided into physical, chemical, biological, ecological engineering and a combination of these technologies. Some examples of these methods are listed in Table 1. Physical and chemical technologies are widely used in high-salinity wastewater treatment, primarily including evaporation, membrane techniques, such as RO and nanofiltration (NF), ion exchange, advanced oxidation processes and electrochemical techniques (Hou et al. 2019; Liang et al. 2017). However, physical and chemical techniques are associated with some disadvantages, such as high operational costs and difficulty in achieving the expected treatment results. Biological treatment technologies have the advantages of low operational cost, obvious treatment effect and no secondary pollution. Researchers usually change the environment of bacteria to enhance their salt tolerance and halophilism to improve high-salinity wastewater treatment.

Use of biological technologies for treating high-salinity wastewater

Biological technologies eliminate pollutants from wastewater through the reproduction and metabolism of microorganisms that are economical, highly effective, stable and environmentally friendly (Huang et al. 2019). Saline wastewater from industrial and aquaculture activities is frequently contaminated with nutrients and organics; thus, microorganisms are particularly important for the removal of COD and NH_4^+–N under high salinity conditions (Liang et al. 2017). However, high salinity of wastewater leads to osmotic pressure in microbial cells to exceed normal living conditions, and a massive die-off can change the sludge microbial communities (Pollice et al. 2010; Zhang et al. 2019b), which considerably reduces treatment efficiency and limits traditional biological treatment technologies. Biological treatment technologies of high-salinity wastewater generally include aerobic sludge plants (such as the traditional aerobic activated sludge process, aerobic granular sludge, the sequencing batch reaction (SBR) system, biofilms, and biofilters), anaerobic sludge plants, cultivation and domestication of salt-tolerant and halophilic bacteria from high salinity environment. Some examples of these methods are listed in Table 2. These reports have shown the potential use of biological technologies for saline wastewater treatment. For example, Ramaswami et al. (2019) found that fixed-bed reactor

Table 1 Summary of high-salinity wastewater treatment methods

	Type of wastewater	Major contaminants	Techniques	Effectiveness	References
Physical technologies	Simulated Chromium tannery wastewater	Na+, Cl−, $SO_4$2−	NF membrane	–	Yan et al. (2016)
Chemical technologies	Vinyl chloride monomer and polyvinyl chloride manufacturing plant	COD, TDS	Heterogeneous UV-assisted sono-Fenton	COD: 87%	Kakavandi and Ahmadi (2019)
Biological technologies	Mustard tuber wastewater	COD, Na+, Cl−	Microbial fuel cell	COD: 89.0% ± 1.5% BOD: 98.6% ± 2.0%	Zhang et al. (2019a, b, c)
	Synthetic wastewater	COD, TN, TP, NH_4^+–N, NaCl	SBR system	COD: 75% TN, NH_4^+–N: 98.5%	She et al. (2016)
	Landfill site leachate	NH_4^+–N, Cl^-	FBRs (plastic carriers; clay beads)	NH_4^+–N: 97%; 70%	Ramaswami et al. (2019)
Ecological engineering	Tannery wastewater	COD, TDS, TSS	CW	COD: 58–67% BOD: 60–77% TSS: 52–82% NH_4^+–N: 60–86%	Calheiros et al. (2010)
	Synthetic wastewater	Na^+, Cl^-, NO_3^-–N, NH_4^+–N, PO_4^{3-}-P	CW	The best of NH_4^+–N: 85% The best of NO_3^-–N: 68% PO_4^{3-}-P: 100%	Jesus et al. (2017)
Combination technologies	Chemical plant	4, 4′- oxybis	Capacitive deionization-Photocatalysis	EC: 55%	Ye et al. (2019)
	Synthetic wastewater	COD, Na^+, Cl^-	CW-Microbial fuel cell	COD: 64.79 ± 1.15% TP: 86.12 ± 0.38% TN: 70.86 ± 0.49% NH_4^+–N: 79.67 ± 0.45%	Xu et al. (2019)

(FBR) with plastic media fed with NF permeate of landfill leachate yielded NH_4^+–N removals > 97% Muñoz Sierra et al. (2019). reported that anaerobic membrane bioreactors (AnMBR) exhibited a phenol removal of 96% at 26 g Na^+/L. In this mini-review, we reviewed the use of biotechnology to treat high-salinity wastewater, as well as the function and purification mechanisms of halotolerant and halophilic microorganisms under salt stress.

Aerobic sludge plants

The traditional activated sludge process has been used in wastewater biological treatment for more than a century (Bengtsson et al. 2019) and can be directly used for treating wastewater with salinity below 10 g/L NaCl, regarding that most of microorganisms in activated sludge are non-halophilic which cannot survive with the salinity exceed 10 g/L (Tan et al. 2019). The properly domesticated microbes can adapt to high salt conditions (Hamoda and Al-Attar 1995). Aloui et al. (2009) described that under NaCl concentrations up to 4% (w/v) and organic loading rates up to 855 mg COD/L/d, the fish processing saline wastewater was efficiently treated with acclimatized activated sludge. At 2.0 wt% salinity, the SBR system inoculated with activated sludge achieved a 95% removal rate of COD, biochemical oxygen demand (BOD), NH_4^+–N and total phosphorus (TP) with *Candidate_division_TM7* as the dominant bacteria genus (Zhao et al. 2016). Some studies also reported the removal of heavy metals under high-salinity conditions by the aerobic activated sludge process. Industrial saline wastewaters contain heavy metals, such as refinery effluents (Soda et al. 2011). Zhang et al. (2019b) studied the removal of selenite (Se^{4+}) in artificial wastewater under high-salinity conditions of 70 g/L by using activated sludge in aerobic SBRs. The reactor removed soluble Se with relatively high efficiency in the beginning of the experiment. But the experiment failed because the activated sludge was not adapted to high salinity, and the removal efficiency was recovered from the 20th batch. di Biase et al. (2020) studied the removal of ammonia, thiocyanate, and cyanate in an aerobic up-flow submerged attached growth reactor to treat gold mine wastewater. The ammonia remove efficiency was achieved over 98% and the residual cyanate concentrations were below 2 mg-SCN-N/L.

Compared with the traditional activated sludge process, aerobic granular sludge (AGS) is denser, more compact and spherical, thereby occupying a lower footprint (Bengtsson et al. 2019; Beun et al. 1999). The effectiveness and

Table 2 Use of biological technologies for high-salinity wastewater treatment

Treatment methods	Type of wastewater	Operation parameters	Removal efficiency	Comments	References
SBR system	Synthetic wastewater	HRT: 14.9 h	COD: 75% TN, NH_4^+–N: 98.5%	In the salt concentration range of 5 to 37.7 g/L, the increase of salinity did not inhibit ammonium oxidation and nitrite denitrification	She et al. (2016)
FBRs: plastic carriers; clay beads	Landfill site leachate	Upflow velocities: 8 or 12 m/h	NH_4^+–N: 97%; 70%	Increased in chloride content did not have any observable detrimental effects on the performance of the reactors	Ramaswami et al. (2019)
AnMBRs	Phenolic wastewater	HRT: 7 d SRT: 40 ± 2 d	Phenol: 96% (26 g Na^+/L)	AnMBR shows higher stability than UASB under high-salinity conditions	Muñoz Sierra et al. (2019)
Aerobic SBR	Tanneries effluents	HRT: 2.5–5 d	The best of COD: 95%, PO_4^{3-}: 93%, TKN: 96%, SS: 92%	The halophilic bacteria responsible for nitrogen removal were most sensitive to modification of HRT, OLR, and salinity	Lefebvre et al. (2005)
Marine purple phototrophic bacteria cultivation	High salinity domestic wastewater	HRT: 22.4–25 h SRT: 2.3–3.9 d	COD: 86 ± 1.7% TN: 62 ± 2.0% TP: 51 ± 2.6%	The adapted bacteria community was halophilic, with batch tests having a broad optimum between 20 and 70 mS/cm	Hulsen et al. (2019)
Airlift SBR	Synthetic wastewater	OLR: 0.18–0.36 g/(L/d) HRT: 8 h SRT: 20d	COD: 90.9 ± 0.8% NH_4^+–N: 72.6 ± 4.0%	Halophile sediment granulation in estuaries resolved the problem of sludge loss in high salinity environment	Huang et al. (2019)

stability of AGS in treating salt-containing wastewater has been evaluated in some studies. Pronk et al. (2014) evaluated the effect of stepwise increased salinity levels on nitrification, denitrification, nitrous oxide emissions, phosphate, and COD removal from synthetic wastewater. Ammonia oxidation was not affected at any salt concentration, but nitrite oxidation and phosphate removal were severely inhibited at 20 g Cl^-/L. Hou et al. (2019) followed the performance and microbial characteristics of AGS under different salinities and alternating salinities. These researchers found that alternating salinity not only increased the COD removal efficiency but also generated a high concentration of granular biomass with good settling ability.

The effectiveness of biofilms and biofilters to treat high-salt wastewater has been discussed in several studies. Aslan and Simsek (2012) investigated the NO_2–N/NO_x–N ratio and NH_4^+–N removal efficiencies under various NaCl concentrations (0–40 g/L) under constant environmental conditions in a submerged biofilter reactor. These researchers found that the removal rate of NH_4^+–N (from 92 to 95%) increased with a small increase in salt concentration (1 g/L NaCl), and over this concentration, each NaCl addition induced NH_4^+–N oxidation. Navada et al. (2019) found that the ammonia oxidation capacity of moving bed biofilm reactors (MBBRs) was weakly influenced by the salinity increase rate, and the microbial community composition changed least for the largest salinity increment.

Anaerobic sludge plants

Anaerobic processes seem more attractive than aerobic processes because the processes consume little energy without aeration and can generate new energy in the form of methane or fuel alcohols (Xiao and Roberts 2010). Lefebvre et al. (2006) used an upflow sludge blanket reactor (UASB) reactor to study the anaerobic digestion of tannery soak liquor, and 78% COD removal efficiency was achieved at a TDS concentration of 71 g/L. Chung et al. (2009) observed approximately 100% removal efficiency of perchlorate and nitrate after 35 days of operation with denitrifying upflow packed-bed bioreactor (10% w/v NaCl concentration). Shi et al. (2014) treated pharmaceutical wastewater with high salinity through sequential anaerobic–aerobic treatment process and achieved 91.8–94.7% COD removal efficiency. Carrera et al. (2019) studied the development and stability of AGS in two SBR reactors treating fish canning wastewater. Their results demonstrated that the presence of anaerobic feeding/reaction phase increased the removal efficiency of organics (80–90%), which was higher than that using complete aerobic phase (75–85%).

In 1995, anaerobic ammonia oxidation (anammox) was first discovered unexpectedly in a denitrification fluidized bed reactor (Mulder et al. 1995). Anammox refers to the microbial anaerobic oxidation of ammonium by nitrite (NO_2^-), which forms N_2; it is a chemoautotrophic process (Reitner and Thiel 2011; Strous et al. 1998). The anammox process has the potential to treat saline wastewater, as studies have been conducted in the Black Sea, Golfo Dulce, and the tropical east Pacific, which showed that anammox was the main pathway to remove active nitrogen from the ocean (Dalsgaard et al. 2003; Kuypers et al. 2003; Lam et al. 2009). Numerous studies have indicated that the processes related to anammox have been successfully applied to treat saline wastewater. We summarized two strategies to treat saline wastewater with high ammonia nitrogen through the anammox process: (1) acclimation of freshwater-derived anammox bacteria (FAB) and (2) enrichment of marine anammox bacteria (MAB) from salt lakes or marine sediments.

Acclimation of FAB to the saline environment is a practical strategy to treat saline wastewater with high ammonia nitrogen (Li et al. 2018b). Jin et al. (2011) demonstrated that the anammox upflow anaerobic sludge blanket (UASB) reactor performed well under 30 g NaCl /L in the continuous flow. Gonzalez-Silva et al. (2017) found that stepwise adaptation of FAB from 0 to 3 g NaCl /L took 153 days while taking only 40 days from 3 to 30 g NaCl /L, and the dominant genera were shifted from *Candidatus Brocadia fulgida* to *Ca. Kuenenia stuttgartiensis* was observed at 3 g NaCl /L. The nitritation-anammox process (SNAP) system was reported to be able to treat saline (3%) ammonium rich (185 mg/L) wastewater after gradual adaptation, and *Kuenenia* (anammox), *Nitrosomonas* (ammonia oxidizing bacteria, AOB) and *Nitrosovibrio* (AOB) bacteria were salt adaptable microbes (Ge et al. 2019).

Nakajima et al. (2008) first successfully established an enrichment culture of MAB in a column-type reactor. Li et al. (2018a, b, c) reported that the nitrogen removal performance of MAB in SBR was enhanced with Mn^{2+} and Ni^{2+} addition. Rios-Del Toro et al. (2017) raised a novel upflow anaerobic sediment trapped (UAST) reactor for enrichment of MAB and realized high nitrogen removal efficiencies ($>95\%$). The results obtained by these researchers indicated that *Candidatus Kuenenia* and *Candidatus Anammoximicrobium* had great potential for removing NH_4^+–N. These studies suggest that MAB can be applied to the treatment and recovery of high-salinity wastewater in the future.

Cultivation and domestication of salt-tolerant and halophilic bacteria

According to the microorganisms' requirements for salt concentration classification, true halophilic organisms must grow with salt concentrations >3 M NaCl, whereas salt-tolerant organisms do not depend on salt for growth but can tolerate appreciable salt concentrations (<1 M NaCl) (Mokashe et al. 2018).

The physiological and biochemical mechanisms of salt-tolerant and halophilic bacteria to salt stress are complex. We are reviewed from three aspects: (1) maintain the balance of osmotic pressure. Mostly extremely halophilic archaea and bacteria accumulate compatible solutes (organic solutes: trehalose, alanine, proline, glycine betaine), maintain high inorganic solute concentrations (K^+, Mg^{2+}, Ca^{2+}), or elevate the anionic phospholipid proportion of the cellular membrane to maintain the hydration state of the cytoplasmic membrane (Mokashe et al. 2018; Mukhtar et al. 2019; Nath 2016). Compatible solutes are mainly neutral but polar compounds that are easily soluble in water without interfere with cell metabolism (Sharma et al. 2016) and they also have protein-stabilizing properties that support the correct folding of peptides inside and outside the cell under deformed conditions (Street et al. 2006). Patel et al. (2018) reported that a halophilic bacteria strain *Exiguobacterium profundum* PHM11 accumulated L-proline to tolerate salinity. (2) Maintain enzyme activities by salinity. Most enzymes of halobacteria have robust activity and stability under hypersaline conditions and lose activity at salt concentrations lower than 2 M (Zhuang et al. 2010). Halophilic bacteria have been isolated from different marine and hypersaline environments by Setati (2010). These organisms have been shown to produce a wide array of hydrolytic enzymes, which can not only maintain activity at high NaCl concentrations but also have high resistance to denaturation. (3) Produce exopolysaccharides (EPS) appear to prevent injury from free radicals. The EPS have unique water holding and cementing properties, which can enhance cell water retention and protect bacteria from hydric stress and water potential fluctuations (Sharma et al. 2016). Boujida et al. (2018) isolated ten halophilic strains from different hypersaline environments, and all the halophilic bacteria EPS had high emulsifying and antioxidant activities. Singh et al. (2019) also reported the EPS obtained from a strain of halophilic bacterial has a potential as a natural antioxidant.

The treatment of high-salinity wastewater in a biological reactor acclimates common activated sludge by gradually increasing the salinity of wastewater, which undoubtedly increases the treatment time and cost. Halophiles prefer salt and thrive on saline or hypersaline environments. The cultivation and domestication of salt-tolerant and halophilic bacteria growing in extreme high-salinity environments (such as salt lakes, bay salt fields, saline-alkali soils, and pickled food factories) used directly to treat high-salinity wastewater is currently the research hotspot. A strain of *Halomonas*, isolated from coastal sediments, was able to anaerobically degrade 100% of Reactive Brilliant Red K-2BP in the presence of 10–15% NaCl (Guo et al. 2008). Abou-Elela et al. (2010) isolated a salt-tolerant microorganism (*Staphylococcus xylosus*) from a vegetable pickled plant wastewater and they found that the COD removal efficiency was up to 88% when *S. xylosus* was applied as solo inoculum for biodegradation in the case study to treat vegetable pickled acid wastewater with 7.2% salinity. Wu et al. (2013) adopted halophilic microorganisms (*Bacillus sp.* strain) in the aerobic process to treat pretreated wastewater in ethyl chloride production with 4% NaCl and achieved 58.3% COD removal. Maharja et al. (2017) used halophilic bacteria in sequential oxic-anoxic bioreactor to remove dissolved organics and suspended soilds from tannery saline soak liquor. Tan et al. (2017) found a good biodegradability of the domesticated marine activated sludge in treating the industrial phenolic waster, and the removal of phenol, COD and NH_4^+–N achieved 99%, 80% and 68%. Halophilic purple phototrophic bacteria (PPB) isolated from Brisbane river sediments were reported to be able to remove COD, nitrogen, and phosphorus from high salinity domestic wastewater (Hulsen et al. 2019). These observations indicate that biological treatment techniques inoculated with specific halophilic microorganisms provide a promising avenue for the treatment of saline wastewater.

Future recommendations

Published investigation on the biotreatment of high-salinity wastewater indicated that the cultivation and domestication of salt-tolerant and halophilic microorganisms could be a promising technique. However, unfortunately, study on the practical manufacturing wastewater in saline conditions is scarce. Synthetic wastewater has single pollutant component and low salt concentration compared to actual wastewater. Therefore, it is necessary to characterize salt-tolerant or halophilic strains able to degrade contaminant in actual high salinity wastewater and future efforts are required to transition from lab to on field applications.

Many researchers studied the removal efficiency of different industrial sectors by biotreatment technologies. Most of them focus on the traditional high salinity wastewater resources such as curriers and food processing industries, however, different target pollutants in different types of high-salt wastewater. High-salinity wastewater from many industries such as the nuclear industries, petroleum and natural gas extraction, and mining has not been studied, therefore shock loading from different industrial sectors is warranted to enrich biological treatment process for efficient removal of targeted contaminants under high salinity conditions.

Many studies involving biodegradation of specific compounds by the pure and mixed culture of microbes under high-salinity conditions has been conducted. But, the complete degradation pathway, microbial catabolic enzymes involved in the degradation process and the interactions between salt, specific contaminants and microbes are still unknown. Identification and development of bacterial metabolic enzymes and their corresponding degradation pathway under high-salinity conditions are strongly recommended for future study.

Conclusion

Biological technologies are resource-saving and environmentally friendly and have been widely employed in different types of wastewater treatment. Saline wastewaters from different sources usually contain complex pollutants, such as NaCl, and high concentrations of various salts, organic compounds, heavy metals, pesticides, antibiotics and so on. These pollutants can cause land degradation, water quality deterioration and serious problems related to agricultural development. The current status and potential of biological treatment of high-salinity wastewaters were reviewed in this paper. Although high salinity inhibits the growth of microbes, prior studies have shown that the acclimated microorganisms can gradually adapt to the environment of high salinity and can be used to treat saline wastewater. However, more studies are needed to investigate the different types of target contaminants and the interactions between salt and specific contaminants in activated sludge. In addition, it is suggested to carry out the purification culture and domestication of salt-tolerant and halophilic bacteria under practical conditions in future research.

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Compliance with ethical standards

Conflict of interest Authors declare no conflict of interest/competing interests.

References

Abdel Wahed MSM, Mohamed EA, Wolkersdorfer C, El-Sayed MI, M'nif A, Sillanpää M (2015) Assessment of water quality in surface waters of the Fayoum watershed. Egypt Environ Earth Sci 74:1765–1783. https://doi.org/10.1007/s12665-015-4186-0

Abou-Elela SI, Kamel MM, Fawzy ME (2010) Biological treatment of saline wastewater using a salt-tolerant microorganism. Desalination 250:1–5. https://doi.org/10.1016/j.desal.2009.03.022

Akan JC, Moses VOO, Abah J (2007) Assessment of tannery industrial effluents from Kano metropolis, Kano state, Nigeria. J Appl Sci 7:2788–2793. https://doi.org/10.3923/jas.2007.2788.2793

Aloui F, Khoufi S, Loukil S, Sayadi S (2009) Performances of an activated sludge process for the treatment of fish processing saline wastewater. Desalination 246:389–396. https://doi.org/10.1016/j.desal.2008.03.062

Aslan S, Simsek E (2012) Influence of salinity on partial nitrification in a submerged biofilter. Bioresour Technol 118:24–29. https://doi.org/10.1016/j.biortech.2012.05.057

Bengtsson S, de Blois M, Wilen BM, Gustavsson D (2019) A comparison of aerobic granular sludge with conventional and compact biological treatment technologies. Environ Technol 40:2769–2778. https://doi.org/10.1080/09593330.2018.1452985

Beun JJ, Hendriks A, Van Loosdrecht MC, Morgenroth E, Wilderer PA, Heijnen JJ (1999) Aerobic granulation in a sequencing batch reactor. Water Res 33:2283–2290. https://doi.org/10.1016/S0043-1354(98)00463-1

Boujida N, Palau M, Charfi S, El Moussaoui N, Manresa A, Minana-Galbis D, Senhaji NS, Abrini J (2018) Isolation and characterization of halophilic bacteria producing exopolymers with emulsifying and antioxidant activities. Bioc Agric Biotechnol 16:631–637. https://doi.org/10.1016/j.bcab.2018.10.015

Calheiros CS, Quiterio PV, Silva G, Crispim LF, Brix H, Moura SC, Castro PM (2012) Use of constructed wetland systems with *Arundo* and *Sarcocornia* for polishing high salinity tannery wastewater. J Environ Manag 95:66–71. https://doi.org/10.1016/j.jenvman.2011.10.003

Calheiros CSC, Teixeira A, Pires C, Franco AR, Duque AF, Crispim LFC, Moura SC, Castro PML (2010) Bacterial community dynamics in horizontal flow constructed wetlands with different plants for high salinity industrial wastewater polishing. Water Res 44:5032–5038. https://doi.org/10.1016/j.watres.2010.07.017

Carrera P, Campo R, Mendez R, Di Bella G, Campos JL, Mosquera-Corral A, Val Del Rio A (2019) Does the feeding strategy enhance the aerobic granular sludge stability treating saline effluents? Chemosphere 226:865–873. https://doi.org/10.1016/j.chemosphere.2019.03.127

Cassel F, Sharma S (2018) Delocalization of salt solution in a semiarid farmland topsoil. Water Air Soil Pollut. https://doi.org/10.1007/s11270-018-3905-z

Chen GH, Chui HK, Wong CL, Tang DTW, Lu H, Jiang F, van Loosdrecht MC (2012) An innovative triple water supply system and a novel SANI® process to alleviate water shortage and pollution problem for water-scarce coastal areas in China. J Water Sustain 2:121–129

Chung J, Shin S, Oh J (2009) Characterization of a microbial community capable of reducing perchlorate and nitrate in high salinity. Biotechnol Lett 31:959–966. https://doi.org/10.1007/s10529-009-9960-1

Dalsgaard T, Canfield DE, Petersen J, Thamdrup B, Acuna-Gonzalez J (2003) N_2 production by the anammox reaction in the anoxic water column of Golfo Dulce, Costa Rica. Nature 422:606–608. https://doi.org/10.1038/nature01526

di Biase A, Wei V, Kowalski MS, Bratty M, Hildebrand M, Jabari P, Oleszkiewicz JA (2020) Ammonia, thicyanate, and cyanate removal in an aerobic up-flow submerged attached growth reactor treating gold mine wastewater. Chemosphere 243:125395. https://doi.org/10.1016/j.chemosphere.2019.125395

Ezekwe IC, Ezekwe AS, Chima GN (2013) Metal loadings and alkaline mine drainage from active and abandoned mines in the Ivo River basin area of Southeastern Nigeria. Mine Water Environ 32:97–107. https://doi.org/10.1007/s10230-013-0220-1

Fabiani C, Ruscio F, Spadoni M, Pizzichini M (1996) Chromium (III) salts recovery process from tannery wastewaters. Desalination 108:183–191. https://doi.org/10.1016/S0011-9164(97)00026-X

Fang H, Liu G, Kearney M (2005) Georelational analysis of soil type, soil salt content, landform, and land use in the Yellow River Delta, China. Environ Manag 35:72–83. https://doi.org/10.1007/s00267-004-3066-2

Fent K, Weston AA, Caminada D (2006) Ecotoxicology of human pharmaceuticals. Aquat Toxicol 76:122–159. https://doi.org/10.1016/j.aquatox.2005.09.009

Ge CH, Dong Y, Li H, Li Q, Ni SQ, Gao B, Xu S, Qiao Z, Ding S (2019) Nitritation-anammox process—a realizable and satisfactory way to remove nitrogen from high saline wastewater. Bioresour Technol 275:86–93. https://doi.org/10.1016/j.biortech.2018.12.032

Gonzalez-Silva BM, Ronning AJ, Andreassen IK, Bakke I, Cervantes FJ, Østgaard K, Vadstein O (2017) Changes in the microbial community of an anammox consortium during adaptation to marine conditions revealed by 454 pyrosequencing. Appl Microbiol Biot 101:5149–5162. https://doi.org/10.1007/s00253-017-8160-5

Guo J, Zhou J, Wang D, Tian C, Wang P, Uddin MS (2008) A novel moderately halophilic bacterium for decolorizing azo dye under high salt condition. Biodegradation 19(1):15–19. https://doi.org/10.1007/s10532-007-9110-1

Hamoda MF, Al-Attar IMS (1995) Effects of high sodium chloride concentrations on activated sludge treatment. Water Sci Technol 31:61–72. https://doi.org/10.1016/0273-1223(95)00407-e

Hossain L, Sarker SK, Khan MS (2018) Evaluation of present and future wastewater impacts of textile dyeing industries in Bangladesh. Environ Dev 26:23–33. https://doi.org/10.1016/j.envdev.2018.03.005

Hou M, Li W, Li H, Li C, Wu X, Liu Y (2019) Performance and bacterial characteristics of aerobic granular sludge in response to alternating salinity. Int Biodeter Biodegr 142:211–217. https://doi.org/10.1016/j.ibiod.2019.05.007

Hu Q, Yang Y, Han S, Wang J (2019) Degradation of agricultural drainage water quantity and quality due to farmland expansion and water-saving operations in arid basins. Agr Water Manag 213:185–192. https://doi.org/10.1016/j.agwat.2018.10.019

Huang JL, Wang HH, Alam F, Cui YW (2019) Granulation of halophilic sludge inoculated with estuarine sediments for saline wastewater treatment. Sci Total Environ 682:532–540. https://doi.org/10.1016/j.scitotenv.2019.05.197

Hulsen T, Hsieh K, Batstone DJ (2019) Saline wastewater treatment with purple phototrophic bacteria. Water Res 160:259–267. https://doi.org/10.1016/j.watres.2019.05.060

Jadeja RN, Tewari A (2007) Effect of soda ash industry effluent on bioaccumulation of metals by seaweeds of coastal region of Gujarat, India. J Hazard Mater 147:148–154. https://doi.org/10.1016/j.jhazmat.2006.12.060

Jesus JM, Calheiros CS, Castro PM, Borges MT (2014) Feasibility of *Typha latifolia* for high salinity effluent treatment in constructed wetlands for integration in resource management systems. Int J Phytoremediat 16:334–346. https://doi.org/10.1080/15226514.2013.773284

Jesus JM, Cassoni AC, Danko AS, Fiuza A, Borges MT (2017) Role of three different plants on simultaneous salt and nutrient reduction from saline synthetic wastewater in lab-scale constructed wetlands. Sci Total Environ 579:447–455. https://doi.org/10.1016/j.scitotenv.2016.11.074

Jin RC, Ma C, Mahmood Q, Yang GF, Zheng P (2011) Anammox in a UASB reactor treating saline wastewater. Process Saf Environ 89:342–348. https://doi.org/10.1016/j.psep.2011.05.001

Kakavandi B, Ahmadi M (2019) Efficient treatment of saline recalcitrant petrochemical wastewater using heterogeneous UV-assisted sono-Fenton process. Ultrason Sonochem 56:25–36. https://doi.org/10.1016/j.ultsonch.2019.03.005

Karimov A, Qadir M, Noble A, Vyshpolsky F, Anzelm K (2009) Development of magnesium-dominant soils under irrigated agriculture in Southern Kazakhstan. Pedosphere 19:331–343. https://doi.org/10.1016/S1002-0160(09)60124-7

Kartal B, Koleva M, Arsov R, van der Star W, Jetten MS, Strous M (2006) Adaptation of a freshwater anammox population to high salinity wastewater. J Biotechnol 126:546–553. https://doi.org/10.1016/j.jbiotec.2006.05.012

Kuypers MMM, Sliekers AO, Lavik G, Schmid M, Jorgensen BB, Kuenen JG, Sinninghe Damste JS, Strous M, Jetten MSM (2003) Anaerobic ammonium oxidation by anammox bacteria in the Black Sea. Nature 422:608–611. https://doi.org/10.1038/nature01472

Lam P, Lavik G, Jensen MM, van de Vossenberg J, Schmid M, Woebken D, Gutiérrez D, Amann R, Jetten MSM, Kuypers MMM, Kari DM (2009) Revising the nitrogen cycle in the Peruvian oxygen minimum zone. Proc Natl Acad Sci USA 106:4752–4757. https://doi.org/10.1073/pnas.0812444106

Lee KY, Kim KW, Park M, Kim J, Oh M, Lee EH, Chuang DY, Moon JK (2016) Novel application of nanozeolite for radioactive cesium removal from high-salt wastewater. Water Res 95:134–141. https://doi.org/10.1016/j.watres.2016.02.052

Lefebvre O, Moletta R (2006) Treatment of organic pollution in industrial saline wastewater: a literature review. Water Res 40:3671–3682. https://doi.org/10.1016/j.watres.2006.08.027

Lefebvre O, Vasudevan N, Torrijos M, Thanasekaran K, Moletta R (2005) Halophilic biological treatment of tannery soak liquor in a sequencing batch reactor. Water Res 39:1471–1480. https://doi.org/10.1016/j.watres.2004.12.038

Lefebvre O, Vasudevan N, Torrijos M, Thanasekaran K, Moletta R (2006) Anaerobic digestion of tannery soak liquor with an aerobic post-treatment. Water Res 40:1492–1500. https://doi.org/10.1016/j.watres.2006.02.004

Li B (2010) Soil salinization. Desertification and its control in China. Springer, Berlin, pp 263–298

Li J, Feng L, Qiang Z, Dong H, Wang D (2018a) Enhanced performance and kinetics of marine anammox bacteria (MAB) treating nitrogen-rich saline wastewater with Mn (II) and Ni (II) addition. Bioresour Technol 249:1085–1091. https://doi.org/10.1016/j.biortech.2017.10.101

Li J, Qi P, Qiang Z, Dong H, Gao D, Wang D (2018b) Is anammox a promising treatment process for nitrogen removal from nitrogen-rich saline wastewater? Bioresour Technol 270:722–731. https://doi.org/10.1016/j.biortech.2018.08.115

Li Y, Wang Y, Gao Y, Zhao H, Zhou W (2018c) Seawater toilet flushing sewage treatment and nutrients recovery by marine bacterial-algal mutualistic system. Chemosphere 195:70–79. https://doi.org/10.1016/j.chemosphere.2017.12.076

Liang Y, Zhu H, Bañuelos G, Yan B, Zhou Q, Yu X, Cheng X (2017) Constructed wetlands for saline wastewater treatment: a review. Ecol Eng 98:275–285. https://doi.org/10.1016/j.ecoleng.2016.11.005

Liang Y, Cheng X, Zhu H, Shutes B, Yan B, Zhou Q, Yu X (2018) Historical Evolution of Mariculture in China During Past 40 Years and Its Impacts on Eco-environment. Chin Geogr Sci 28:363–373. https://doi.org/10.1007/s11769-018-0940-z

Liu X, Dai J, Wu D, Jiang F, Chen G, Chui H-K, van Loosdrecht MCM (2016) Sustainable application of a novel water Cycle using seawater for toilet flushing. Engineering 2:460–469. https://doi.org/10.1016/j.eng.2016.04.013

Lutz BD, Lewis AN, Doyle MW (2013) Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development. Water Resour Res 49:647–656. https://doi.org/10.1002/wrcr.20096

Maharja P, Mahesh M, Chitra C, Kalaivani D, Srividya R, Swarnalatha S, Sekaran G (2017) Sequential oxic-anoxic bio reactor for the treatment of tannery saline wastewater using halophilic and filamentous bacteria. J Water Process Eng 18:47–57. https://doi.org/10.1016/j.jwpe.2017.03.011

Missimer TM, Maliva RG (2018) Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination 434:198–215. https://doi.org/10.1016/j.desal.2017.07.012

Mokashe N, Chaudhari B, Patil U (2018) Operative utility of salt-stable proteases of halophilic and halotolerant bacteria in the biotechnology sector. Int J Biol Macromol 117:493–522. https://doi.org/10.1016/j.ijbiomac.2018.05.217

Mukhtar S, Ahmad S, Bashir A, Mehnaz S, Mirza MS, Malik KA (2019) Identification of plasmid encoded osmoregulatory genes from halophilic bacteria isolated from the rhizosphere of halophytes. Microbiol Res 228:126307. https://doi.org/10.1016/j.micres.2019.126307

Mulder A, van de Graaf AA, Robertson LA, Kuenen JG (1995) Anaerobic ammonium oxidation discovered in a denitrifying fluidized bed reactor. FEMS Microbiol Ecol 16:177–184. https://doi.org/10.1016/0168-6496(94)00081-7

Muñoz Sierra JD, Oosterkamp MJ, Wang W, Spanjers H, van Lier JB (2019) Comparative performance of upflow anaerobic sludge blanket reactor and anaerobic membrane bioreactor treating phenolic wastewater: Overcoming high salinity. Chem Eng J 366:480–490. https://doi.org/10.1016/j.cej.2019.02.097

Na L, Genxu W, Guangsheng L, Yun L, Xiangyang S (2013) The ecological implications of land use change in the Source Regions of the Yangtze and Yellow Rivers, China. Reg Environ Change 13:1099–1108. https://doi.org/10.1007/s10113-013-0419-5

Nakajima J, Sakka M, Kimura T, Furukawa K, Sakka K (2008) Enrichment of anammox bacteria from marine environment for the construction of a bioremediation reactor. Appl Microbiol Biot 77:1159–1166. https://doi.org/10.1007/s00253-007-1247-7

Nath A (2016) Insights into the sequence parameters for halophilic adaptation. Amino Acids 48:751–762. https://doi.org/10.1007/s00726-015-2123-x

Navada S, Vadstein O, Tveten A-K, Verstege GC, Terjesen BF, Mota VC, Venkataraman V, Gaument F, Mikkelsen O, Kamstra A (2019) Influence of rate of salinity increase on nitrifying biofilms. J Clean Prod 238:117835. https://doi.org/10.1016/j.jclepro.2019.117835

Ng KK, Shi X, Tang MKY, Ng HY (2014) A novel application of anaerobic bio-entrapped membrane reactor for the treatment of chemical synthesis-based pharmaceutical wastewater. Sep Purif Technol 132:634–643. https://doi.org/10.1016/j.seppur.2014.06.021

Patel VK, Srivastava R, Sharma A, Srivastava AK, Singh S, Srivastava AK, Kashyap PL, Chakdar H, Pandiyan K, Kalra A, Saxena AK (2018) Halotolerant *Exiguobacterium profundum* PHM11 tolerate salinity by accumulating L-proline and fine-tuning gene expression profiles of related metabolic pathways. Front Microbiol 9:423. https://doi.org/10.3389/fmicb.2018.00423

Pernetti M, Di Palma L (2005) Experimental evaluation of inhibition effects of saline wastewater on activated sludge. Environ Technol 26:695–703. https://doi.org/10.1080/09593330.2001.9619509

Pollice A, Rozzi A, Tomei MC, Di Pinto AC, Limoni N (2010) Monitoring the inhibitory effect of NaCl on anaerobic wastewater treatment processes by the Rantox biosensor. Environ Technol 21:535–544. https://doi.org/10.1080/09593332408618095

Pronk M, Bassin JP, de Kreuk MK, Kleerebezem R, van Loosdrecht MC (2014) Evaluating the main and side effects of high salinity on aerobic granular sludge. Appl Microbiol Biot 98:1339–1348. https://doi.org/10.1007/s00253-013-4912-z

Ramaswami S, Jalal Uddin FM, Behrendt J, Otterpohl R (2019) High-rate nitrification of saline wastewaters using fixed-bed reactors. J Environ Manag 243:444–452. https://doi.org/10.1016/j.jenvman.2019.05.020

Reitner J, Thiel V (2011) Anammox. In: Reitner J, Thiel V (eds) Encyclopedia of geobiology. Springer, Dordrecht, pp 53–53

Rios-Del Toro EE, López-Lozano NE, Cervantes FJ (2017) Up-flow anaerobic sediment trapped (UAST) reactor as a new configuration for the enrichment of anammox bacteria from marine sediments. Bioresour Technol 238:528–533. https://doi.org/10.1016/j.biortech.2017.04.087

Setati ME (2010) Diversity and industrial potential of hydrolase producing halophilic/halotolerant eubacteria. Afr J Biotechnol 9(11):1555–1560. https://doi.org/10.5897/AJB10.051

Sharma A, Vaishnav A, Jamali H, Srivastava AK, Saxena AK, Srivastava AK (2016) Halophilic Bacteria: Potential Bioinoculants for Sustainable Agriculture and Environment Management Under Salt Stress. In: Choudhary D, Varma A, Tuteja N (eds) Plant–microbe interaction: an approach to sustainable agriculture. Springer, Singapore, pp 297–325

She Z, Zhao L, Zhang X, Jin C, Guo L, Yang S, Zhao Y, Gao M (2016) Partial nitrification and denitrification in a sequencing batch reactor treating high-salinity wastewater. Chem Eng J 288:207–215. https://doi.org/10.1016/j.cej.2015.11.102

Shi X, Lefebvre O, Ng KK, Ng HY (2014) Sequential anaerobic–aerobic treatment of pharmaceutical wastewater with high salinity. Bioresour Technol 153:79–86. https://doi.org/10.1016/j.biortech.2013.11.045

Singh S, Sran KS, Pinnaka AK, Choudhury AR (2019) Purification, characterization and functional properties of exopolysaccharide from a novel halophilic *Natronotalea sambharensis* sp. nov. Int J Biol Macromol 136:547–558. https://doi.org/10.1016/j.ijbiomac.2019.06.080

Soda S, Kashiwa M, Kagami T, Kuroda M, Yamashita M, Ike M (2011) Laboratory scale bioreactors for soluble selenium removal from selenium refinery wastewater using anaerobic sludge. Desalination 279(1–3):433–438. https://doi.org/10.1016/j.desal.2011.06.031

Street TO, Bolen DW, Rose GD (2006) A molecular mechanism for osmolyte-induced protein stability. Proc Natl Acad Sci USA 103(38):13997–14002. https://doi.org/10.1073/pnas.0606236103

Strous M, Heijnen JJ, Kuenen JG, Jetten MSM (1998) The sequencing batch reactor as a powerful tool for the study of slowly growing anaerobic ammonium-oxidizing microorganisms. Appl Microbiol Biot 50:589–596. https://doi.org/10.1007/s002530051340

Tan S, Cui C, Hou Y, Chen X, Xu A, Li W, You H (2017) Cultivation of activated sludge using sea mud as seed to treat industrial phenolic wastewater with high salinity. Mar Pollut Bull 114(2):867–870. https://doi.org/10.1016/j.marpolbul.2016.11.026

Tan X, Acquah I, Liu H, Li W, Tan S (2019) A critical review on saline wastewater treatment by membrane bioreactor (MBR) from a microbial perspective. Chemosphere 220:1150–1162. https://doi.org/10.1016/j.chemosphere.2019.01.027

Voutchkov N (2018) Energy use for membrane seawater desalination—current status and trends. Desalination 431:2–14. https://doi.org/10.1016/j.desal.2017.10.033

Wei Y, Zhang SH (2018) Abiostress resistance and cellulose degradation abilities of haloalkaliphilic fungi: applications for saline-alkaline remediation. Extremophiles 22:155–164. https://doi.org/10.1007/s00792-017-0986-3

Wu X, Du YG, Qu Y, Du DY (2013) Ternary cycle treatment of high saline wastewater from pesticide production using a salt-tolerant microorganism. Water Sci Technol 67:1960–1966. https://doi.org/10.2166/wst.2013.072

Xiang JH (2007) Mariculture-related environmental concerns in the People's Republic of China. In: Bert TM (ed) Ecological and genetic implications of aquaculture activities. Methods and technologies in fish biology and fisheries, vol 6. Springer, Dordrecht, pp 219–228

Xiao Y, Roberts DJ (2010) A review of anaerobic treatment of saline wastewater. Environ Technol 31:1025–1043. https://doi.org/10.1080/09593331003734202

Xu F, Ouyang DL, Rene ER, Ng HY, Guo LL, Zhu YJ, Zhou LL, Yuan Q, Miao MS, Wang Q, Kong Q (2019) Electricity production enhancement in a constructed wetland-microbial fuel cell system for treating saline wastewater. Bioresour Technol 288:121462. https://doi.org/10.1016/j.biortech.2019.121462

Xu H, Yang B, Liu Y, Li F, Shen C, Ma C, Tian Q, Song X, Sand W (2018) Recent advances in anaerobic biological processes for textile printing and dyeing wastewater treatment: a mini-review. World J Microb Biot 34:165. https://doi.org/10.1007/s11274-018-2548-y

Yan ZQ, Zeng LM, Li Q, Liu TY, Matsuyama H, Wang XL (2016) Selective separation of chloride and sulfate by nanofiltration for high saline wastewater recycling. Sep Purif Technol 166:135–141. https://doi.org/10.1016/j.seppur.2016.04.009

Yang J, Zhang S, Li Y, Bu K, Zhang Y, Chang L, Zhang Y (2010) Dynamics of saline-alkali land and its ecological regionalization in western Songnen Plain, China. Chin Geogr Sci 20:159–166. https://doi.org/10.1007/s11769-010-0159-0

Yang YN, Sheng Q, Zhang L, Kang HQ, Liu Y (2015) Desalination of saline farmland drainage water through wetland plants. Agr Water Manag 156:19–29. https://doi.org/10.1016/j.agwat.2015.03.001

Ye G, Yu Z, Li Y, Li L, Song L, Gu L, Cao X (2019) Efficient treatment of brine wastewater through a flow-through technology integrating desalination and photocatalysis. Water Res 157:134–144. https://doi.org/10.1016/j.watres.2019.03.058

Zhang L, Fu G, Zhang Z (2019a) Electricity generation and microbial community in long-running microbial fuel cell for high-salinity mustard tuber wastewater treatment. Bioelectrochemistry 126:20–28. https://doi.org/10.1016/j.bioelechem.2018.11.002

Zhang Y, Kuroda M, Arai S, Kato F, Inoue D, Ike M (2019b) Biological treatment of selenate-containing saline wastewater by activated sludge under oxygen-limiting conditions. Water Res 154:327–335. https://doi.org/10.1016/j.watres.2019.01.059

Zhang Y, Kuroda M, Nakatani Y, Soda S, Ike M (2019c) Removal of selenite from artificial wastewater with high salinity by activated sludge in aerobic sequencing batch reactors. J Biosci Bioeng 127:618–624. https://doi.org/10.1016/j.jbiosc.2018.11.002

Zhao Y, Park HD, Park JH, Zhang F, Chen C, Li X, Zhao D, Zhao F (2016) Effect of different salinity adaptation on the performance and microbial community in a sequencing batch reactor. Bioresour Technol 216:808–816. https://doi.org/10.1016/j.biortech.2016.06.032

Zhuang X, Han Z, Bai Z, Zhuang G, Shim H (2010) Progress in decontamination by halophilic microorganisms in saline wastewater and soil. Environ Pollut 158:1119–1126. https://doi.org/10.1016/j.envpol.2010.01.007