

A review of microbial corrosion in reclaimed water pipelines: challenges and mitigation strategies

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ABSTRACT

With the continuous development and expansion of the water reclamation and reuse market, it is vital to ensure water quality safety and stability over the entire water reuse system. Because the quality of reclaimed water is distinct from that of drinking water, it is likely to deteriorate, even after advanced treatment, during distribution and transport. This review identifies the common microbial corrosion in reclaimed water distribution pipelines and end use applications (e.g. industrial cooling system) and the dominant corrosive microorganisms in reclaimed water. The microbial corrosion mechanism and the affecting factors on microbial corrosion are discussed in depth. Moreover, this study also proposes possible strategies for dealing with pipeline microbial corrosion, including the control of the assimilable organic carbon content via coagulation and filtration processes as well as disinfection technologies for microbial inactivation. This study is of great novelty to provide a comprehensive overview of microbial corrosion in reclaimed water distribution and application and point out future directions towards sustainable and long-lasting water reuse.

Key words: control strategies, microbial corrosion, pipeline materials, reclaimed water technology

HIGHLIGHTS

- Reclaimed water technology;
- Microbial corrosion;
- Pipeline materials;
- Control strategies

1. INTRODUCTION

With the increasing environmental pollution in recent years, the concept of ‘green development’ has been put forward. It emphasizes sustainable development via reduced energy consumption, emission reduction, and pollution control, a concept which wastewater treatment and reuse is compatible with. Notably, the use of reclaimed water is becoming increasingly extensive, and it has gradually occupied an indispensable role in many water-deficient cities. In terms of wastewater treatment and reuse processes, existing technologies vary from conventional secondary treatment processes (e.g., activated sludge and biological nutrient removal units) to advanced treatment approaches such as membrane filtration and advanced oxidation processes (Zhang *et al.* 2016). With the development and promotion of treatment technologies, the construction and expansion of reclaimed water pipelines and networks have also come onto a fast track of development.

For instance, by the end of 2019, the total length of the reclaimed water pipe network in China stretched 13,000 km, and the total amount of wastewater treated had reached 46.5 billion cubic meters (m³). Figure 1 shows the change in the length of China’s reclaimed water pipeline and the trend of reclaimed water utilization from 2012 to 2019.

Particularly, the length of the reclaimed water pipeline network in three typical cities (i.e., Beijing, Tianjin, and Shandong) accounted for 50% of the total reclaimed water pipeline length in China. Table 1 shows the top ten cities in China with the length of reclaimed water pipelines by the end of 2019.

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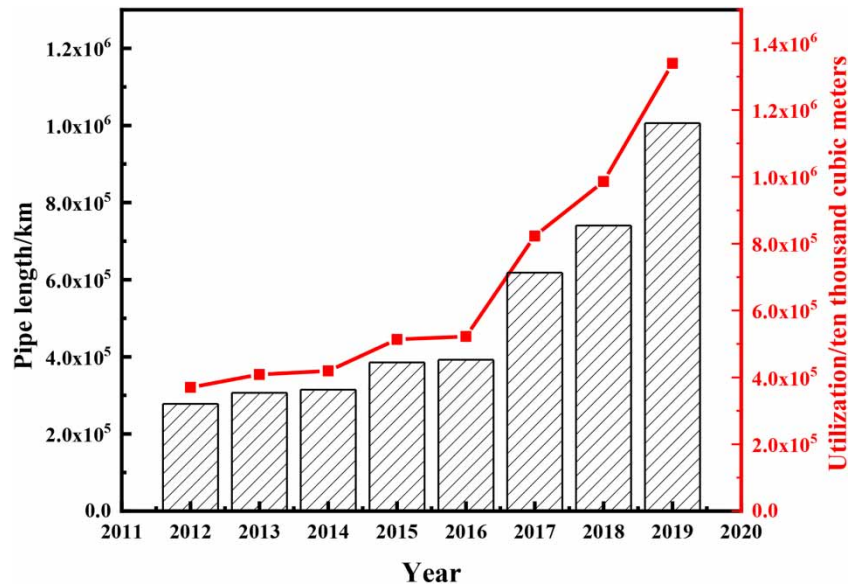


Figure 1 | Changes in the length of China's reclaimed water pipelines and the amount of reclaimed water used from 2012 to 2019 (Data source: Urban and Rural Construction Statistical Yearbook, Ministry of Housing and Urban-Rural Development, 2019).

Table 1 | Reclaimed water pipeline length in typical cities of China

City	Reclaimed water utilization (ten thousand cubic meters/year)	Length of reclaimed water pipeline (km)
Beijing	115,152	2006
Tianjin	26,023	1844
Shandong	152,464	1324
Inner Mongolia	23,948	1180
Jiangsu	98,411	882
Xinjiang	9167	675
Hebei	58,355	599
Yunnan	44,922	582
Henan	54,254	530
Shanxi	19,597	459

Data source: Urban and Rural Construction Statistical Yearbook, Ministry of Housing and Urban-Rural Development, 2019.

Despite the rapid growth in water reuse over the past 20 years worldwide, challenges and difficulties remain. Water safety is key for water reuse, but corrosion of the pipe network during water distribution and transmission remains a challenge, which may hinder further expansion of the water reuse market. Microbial corrosion is one of the most serious pipeline corruptions. The quality of reclaimed water is variable and tends to be unstable owing to higher amounts of dissolved organic carbon (DOC) and nutrients compared with conventional water sources such as surface water and groundwater. Reclaimed water is thus likely to promote the growth of microorganisms during storage and transmission as a rich source of carbon, nitrogen, and phosphorus. Additionally, with the relatively steady temperature throughout the pipeline, the microorganisms in the reclaimed water can adhere to the pipe wall and form a microbial film, which can change the local environment of the pipe wall and thus affect the quality and safety of the water, reduce the service life of the pipe, and can even cause pipe cracks. All these changes can lead to enormous economic losses (Ordóñez *et al.* 2014).

Accordingly, this paper puts forward the review of typical materials of reclaimed water pipelines and the corrosion effects of microorganisms on various materials, analysis and discussion of common corrosive microorganisms in reclaimed water, description of the corrosion mechanism and hazards of microbial pipelines, and discussion of the influence of corrosion factors on microorganisms. This review concludes by suggesting strategies against microbial corrosion and tactics for sustainable water reuse.

2. CURRENT STATUS OF MICROBIAL CORROSION IN RECLAIMED WATER DISTRIBUTION AND APPLICATIONS

While reclaimed water is widely used, microbiological corrosion often exists in both transportation and application of reclaimed water. However, the research on microbiological corrosion in reclaimed water mainly focuses on two parts, including the microbiological corrosion of long-distance transportation pipelines and the microbiological corrosion of circulating cooling systems.

2.1. Microbiological corrosion of long-distance transportation pipelines

The selection of pipeline materials is one of the main considerations of pipeline network construction. Different pipeline materials have different degrees of corrosion resistance to microbial organisms. Figure 2 shows the proportion of different reclaimed water pipeline network materials in typical cities of China (Gan 2014). Ductile iron is the most widely used material for reclaimed water pipes, followed by steel and plastic. The microbiological corrosion of different materials is discussed further in detail.

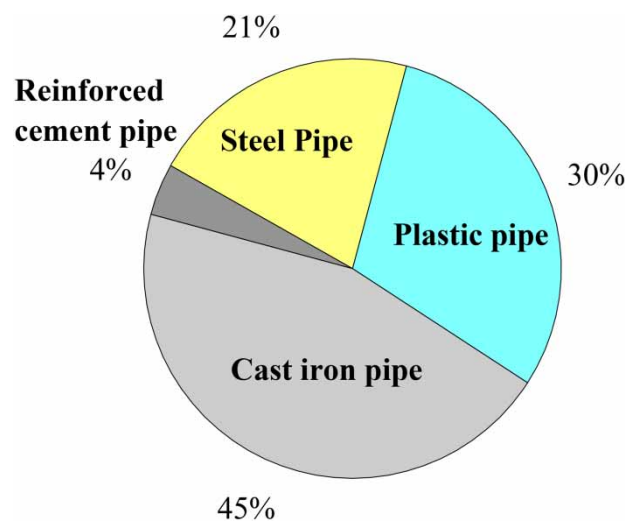


Figure 2 | The proportion of reclaimed water pipe network materials used in typical cities of China.

2.1.1. Metal pipe

Metal pipes were developed early on and have a long history of use. They are widespread because of their reliable mechanical properties and high durability. Yet they are also prone to problems such as pipe wall corrosion, fouling, and the growth of microorganisms.

Cast iron in particular is the most popular pipe material for urban water supply systems, but the exposed metal inner walls can be easily corroded by water, forming corrosion tumors which may affect water quality through the introduction of iron ions and increases in turbidity and color. Additionally, corrosion and scaling on the inner walls of cast iron pipes may facilitate the breeding of bacteria and retention of pollutants, which can result in secondary risks to end users. Zhang *et al.* (2016) found that in reclaimed water pipelines, biofilm at the early stages of formation in cast iron pipes could promote corrosion, while the stably formed biofilm at the later stage shows a protective effect against the surface corrosion of cast iron materials. Moreover, another study has found that while *Thiobacillus ferrooxidans* severely corrodes HT150 cast iron at temperatures of 15, 25, 35, and 45 °C, it has a weaker corrosion ability on HT150 cast iron at 4 °C (Lei & Sun 2017). A study (Yu 2016) has also revealed that the mild compressive strength limit variation indicates that the brittleness of the material remains unaffected by microbial corrosion. The bacterial community significantly promoted cast iron corrosion, which was quantified for the first time in practical reclaimed wastewater, accounting for at least $30.5\% \pm 9.7\%$ of the total weight loss. The partition of yellow and black layers of cast iron corrosion provided more accurate information on morphology and crystal structures for corrosion scales (Zhang *et al.* 2018). At present, the inner walls of pipes are typically lined with cement mortar, epoxy resin, and other inert materials to mitigate the microbial corrosion of cast iron pipes.

Using steel pipe is advantageous because of the material's high pressure resistance, strength, and thin tube wall. However, similar to cast iron pipes, steel pipes can be easily corroded by microorganisms too. For instance, [Zheng \(2012\)](#) found that SRB and iron-oxidizing bacteria (IOB) can significantly affect the electrochemical behavior of Q235 carbon steel, the surface morphology of carbon steel coupons, and the ratio of element composition, while also promoting the corrosion of carbon steel when reclaimed water is presented in circulating cooling water. The corrosion of the cooling water pipeline can thus present a great safety hazard.

Microbial corrosion has been observed in some cases, although stainless steel pipes are generally resistant to corrosion. [Zhou & Zhang \(2019\)](#) found that the corrosion of 2205 duplex stainless steel intensified in a soaking solution containing *Pseudomonas aeruginosa*. However, stainless steel pipes are not the common choice for reclaimed water transmission and distribution because of their high cost.

2.1.2. Non-metallic pipes

Among the non-metallic pipes, reinforced concrete pipes are mainly suitable for large-flow and long-distance water delivery projects. The advantages of reinforced concrete pipes are their ease of production and low cost, while the disadvantages include their heavy weight, hard and brittle texture, and the difficulties associated with their transport and maintenance. Reinforced concrete will also be corroded by microorganisms in the water after immersion. [Rong & Gao \(2019\)](#), who studied the influence of microorganisms on the performance of concrete in a semi-immersed sewage environment, showed that serious aggregate exposure and slurry shedding occurred at the gas-liquid interface of the concrete specimens. They found that corrosion below the gas-liquid interface was more severe than that above, indicating that microorganisms may have a relatively strong effect on concrete corrosion in a reclaimed water environment.

Plastic pipes include those made of polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polybutene (PB), and so on. Among these, PVC pipes and PE pipes are the most common. Plastic pipes are an attractive choice because of their light weight, resistance to corrosion, ease of installation, smooth inner walls without scaling and decent hydraulic performance ([Whelton & Nguyen 2013](#)). Disinfectants are widely used for inhibition of microbial corrosion in plastic pipes, with chlorine disinfectants being the most common because of their ease of preparation, low cost, and satisfactory disinfection capacity ([Weihua 2018](#)). During the inactivation process, however, oxidizing disinfectants may corrode plastic pipes. For example, [Zhang \(2019\)](#) found that chlorine disinfectant led to the corrosion of three pipes. The degree of corrosion is related to the concentration of the disinfectant and the contact time. Thus, the potential effects of oxidizing disinfectants on pipeline corrosion should also be considered when implementing measures to control microbiological corrosion. In recent years, plastic pipes have become more widely used in reclaimed water supply systems, and they have gradually replaced traditional metal pipes owing to their greater advantages. However, the disadvantages of plastic pipes include their poor mechanical properties and low strength. Moreover, they are easily damaged and contain additives that can potentially diminish water quality ([Walter et al. 2011](#)).

2.2. Microbiological corrosion of circulating cooling system

The treated reclaimed water can be transported to major thermal power plants as circulating cooling water. There are two types of circulating cooling water system: closed and open system ([Sarkar 2015](#)). In a closed circulating water system, the recycling of cooling water runs in a completely closed system for reduction of air contact. Therefore, the conditions are adverse to the growth and scaling of aerobic microorganisms. In the open circulating water system, the cooling water is sent to the condenser by the circulating water pump for heat exchange. The heated cooling water is cooled by the cooling tower, and then sent to the condenser by the circulating water pump for circulation. The flow chart of the open circulating cooling water system and the closed circulating water cooling system is shown in [Figure 3](#). Therefore, the open system can easily scale, corrode, and has a serious problem of microbial growth.

Under normal circumstances, there are two main sources for microorganisms in the open circulating cooling water system ([Liang 2019](#)): (i) raw water and supplementary water; (ii) air and precipitation. Raw water and supplementary water are the main sources of microorganisms in the open circulating cooling water system, which directly affect or even determine the type and quantity of microorganisms in the circulating cooling water system. In addition, the circulating water or natural rainwater in the cooling tower also captures a considerable amount of microorganisms, suspended particles and gases from the air that meet the countercurrent during the falling process and enter the cooling water system. The open-circulation cooling water system has environmental

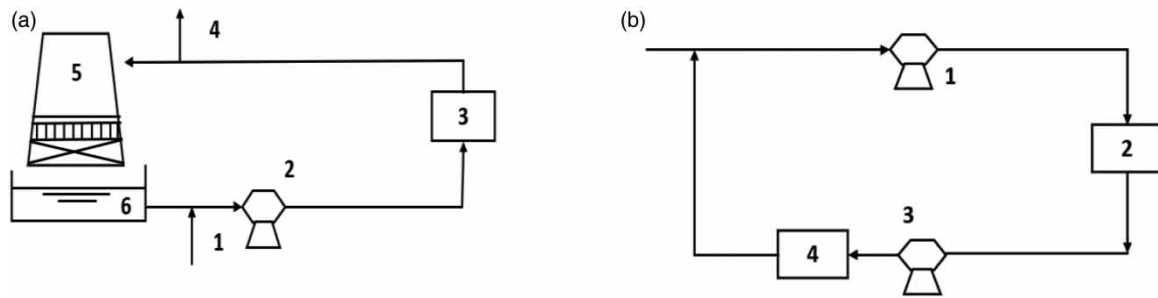


Figure 3 | (a) Open-recycling cooling water system. Notes: 1-Supplementary water; 2-Circulating water pump; 3-Heat exchanger of cooling medium; 4-Discharged effluent; 5-Cooling tower; 6-Cooling water pool (b) Close-recycling cooling water system. Notes: 1-cold water pump; 2-heat exchanger for cooling medium; 3-hot water pump; 4-heat exchanger for cooling hot water.

conditions that are conducive to the growth and reproduction of microorganisms. The circulating water incorporates a large amount of oxygen during the spraying process in the cooling tower, which provides the necessary growth conditions for aerobic microorganisms; the anaerobic conditions in the sedimentary soil provide a shelter for the growth of anaerobic microorganisms; sulfate is also an energy source for anaerobic microorganism such as Sulfate Reducing Bacteria (SRB). A study has previously reported that the water supply has been considered as a major factor affecting cooling water microbial communities based on results from 18 cooling towers using local water sources from 6 geographic locations (Paranjape *et al.* 2019). Another paper also points out the recurrence of biofilm-forming taxa in the basins of cooling towers (Tsao *et al.* 2019). The survey results show that the problems caused by microorganisms during the operation of the circulating cooling water system account for about half of the problems (Geesey & Bryers 2000); it can be seen that the losses caused by microbial problems could lead to substantial economic losses in industry.

3. CORROSIVE MICROORGANISMS IN RECLAIMED WATER

Reclaimed water is transported and distributed by pipelines. Compared with drinking water and other conventional water sources, reclaimed water (i.e., secondary and tertiary effluents) generally contains higher amounts of dissolved organic matter, especially low-molecular-weight compounds and nutrients. These conditions provide a favorable environment for microbial growth and lead to corrosion. Peng (2016) analyzed the community structure of the total corrosion layer in the pipe network of a water reclamation plant and found that the main corrosive bacteria in reclaimed water include SRB, iron-reducing bacteria (IRB), IOB, nitrifying bacteria (NRB), among others. The approximate distribution of these bacteria in the reclaimed water is shown in Figure 4, and their characteristics are summarized in Table 2.

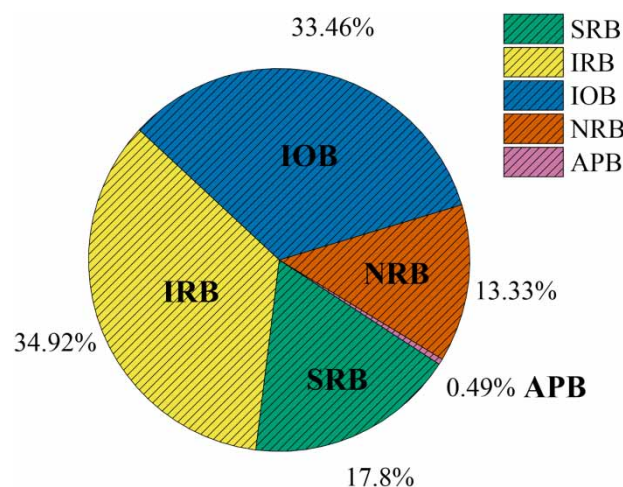


Figure 4 | Proportions of corrosive bacteria detected in reclaimed water. Notes: SRB-sulfate reducing bacteria; IRB-Iron-reducing bacteria; IOB-Iron Oxidizing Bacteria; NRB-Nitrate reducing bacteria; APB-Acid-producing bacteria.

Table 2 | Corrosive microorganisms in reclaimed water

Bacteria	Type	Trait	Effects	References
SRB	Anaerobic	Use H_2 to reduce SO_4^{2-} to S^{2-} ; producing H_2S and FeS	Cathodic depolarization by hydrogen uptake; anodic depolarization by corrosive iron sulfides; Direct iron uptake Acids corrode metal	Li <i>et al.</i> (2014)
IOB	Aerobic	Oxidize Fe^{2+} to Fe^{3+}	Oxidation of iron and manganese (oxides)	Emerson <i>et al.</i> (2010)
IRB	Anaerobic	Reduce Fe^{3+} to Fe^{2+}	Reduction of iron and manganese (oxides)	McBeth & Emerson (2016)
NRB	Anaerobic	Reduce NO_3^- to NH_4^+ ; Oxidize Fe^{2+} to Fe^{3+}	Dissolution of metal	Etique <i>et al.</i> (2014)

3.1. Corrosive microorganisms in reclaimed water

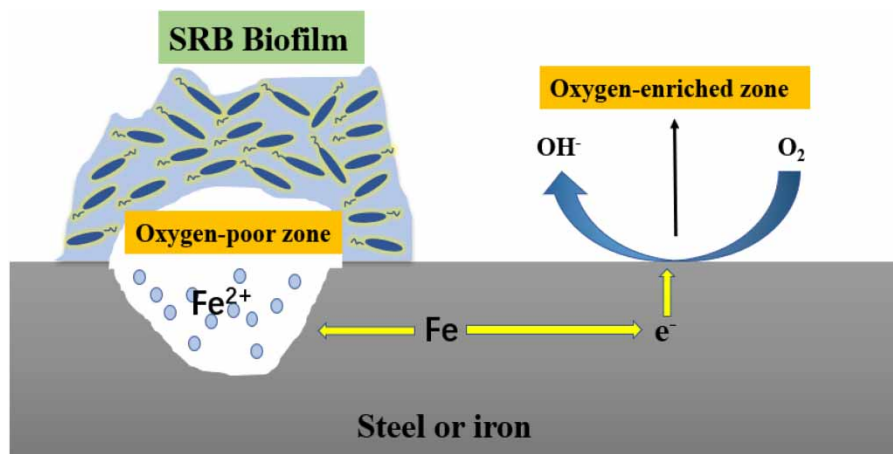
3.1.1. Sulfate-reducing bacteria (SRB)

SRB are among the most common microorganisms contributing to the corrosion of reclaimed water pipelines. And researchers have been studying them for a long time. In 1910, Gaines (Gaines 1910) first described the corrosion of water pipelines by sulfur bacteria and IRB through the presence of a large amount of sulfur. Later, in 1934, Kuhr was the first to use electrochemical methods to study the corrosion process and mechanism of SRB, and proposed the cathode hydrogen depolarization theory (Wolzogen-Kuhr & van der Vlugt 1934).

Reclaimed water pipelines have long been corroded by SRB. Alabbas *et al.* (2013) compared the corrosion rates of X80 pipeline steel for reclaimed water pipes with or without SRB participation and found that the corrosion rate was about five times higher when SRB was present. Wan & Tian (2015) found that SRB in reclaimed water shows corrosive behavior on Q235 carbon steel. The SRB biofilm inhibits the corrosion of carbon steel at the initial stage of immersion, and then promotes the corrosion of carbon steel which manifests as pitting corrosion.

The corrosion mechanism of SRB mainly includes the formation of oxygen concentration battery, cathode depolarization caused by hydrogenase, cathode depolarization caused by FeS , and direct electron transfer theory.

- (i) In the Microbial Corrosion (MIC) process, the adsorption of microorganisms on the surface of the material and the formed biofilm have the characteristics of uneven distribution, which causes the electrochemical properties of the surface of the material to change accordingly, thereby forming an anoxic environment which affects the occurrence of metal corrosion and development. Its corrosion mechanism diagram is shown in Figure 5.
- (ii) In 1934, von Wolzogen Kühr and van der Flugt proposed the cathode depolarization theory. They believe that the hydrogenase in the bacteria can remove the hydrogen produced by the reduction reaction of the

**Figure 5** | The model of oxygen concentration cell (Chen 2015).

carbon steel cathode and use it for its own sulfate reduction. The sulfide produced by metabolism is highly corrosive. The corrosion mechanism is shown in Figure 6.

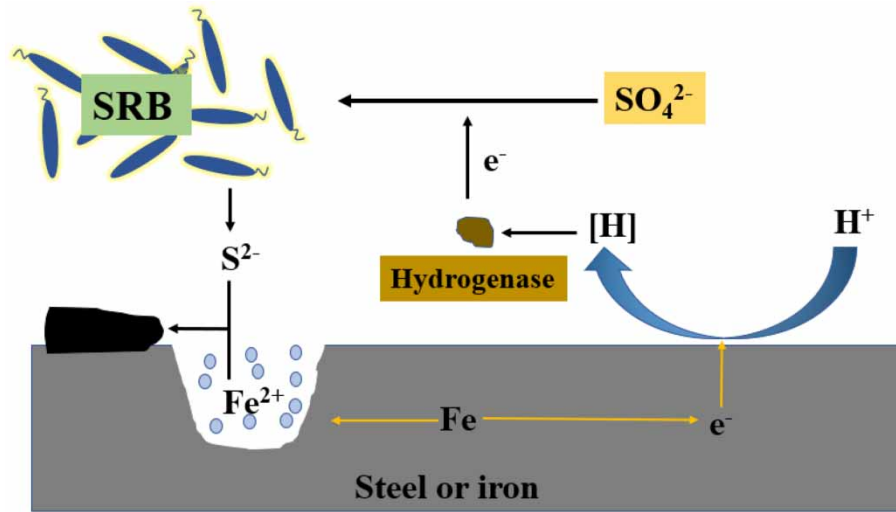


Figure 6 | The model of cathodic depolarization mechanism induced by hydrogenase (Chen 2015).

- (iii) In addition to the hydrogenase cathodic depolarization theory, the formation of catalytically active FeS on the electrode surface can also stimulate the reduction of H^+ to H_2 . This is the theory of cathodic depolarization caused by FeS, and its corrosion mechanism is shown in Figure 7.
- (iv) In recent years, studies have found that electrons from metallic iron are directly obtained to promote the progress of the cathode process in some corrosion processes caused by SRB. Venzlaff *et al.* (2013) studied the corrosion of iron under anaerobic conditions and found that SRB can directly obtain electrons from the metal surface through the corrosion product film of the semiconductor to accelerate the progress of the cathodic reaction. In addition, Sherar *et al.* (2013) found that in the absence of a carbon source, a large number of nanowires are generated on the surface of SRB, which adhere to the metal surface and directly obtain electrons from the metal surface, affecting the progress of the corrosion process. The corrosion mechanism is shown in Figure 8.

SRB can reduce SO_4^{2-} to S^{2-} , and then combine with Fe^{2+} , thereby corroding metal materials. The equation of the reaction mechanism is shown in Equation (1).

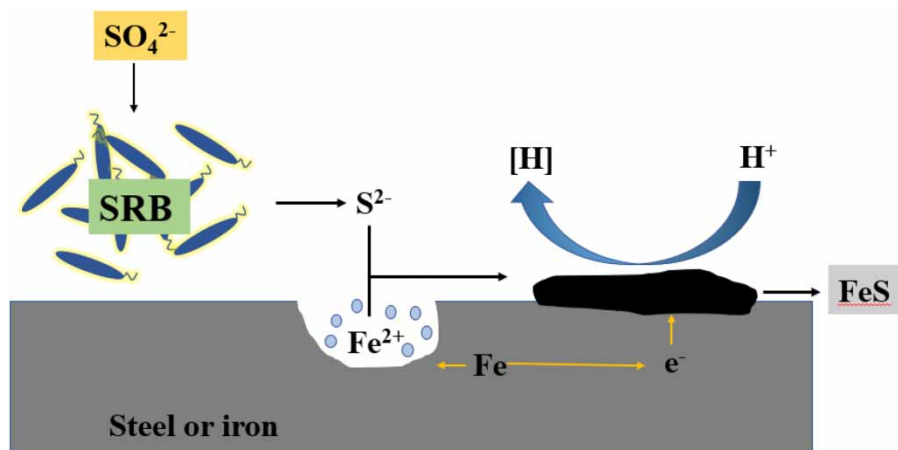


Figure 7 | The model of cathodic depolarization mechanism induced by FeS (Chen 2015).

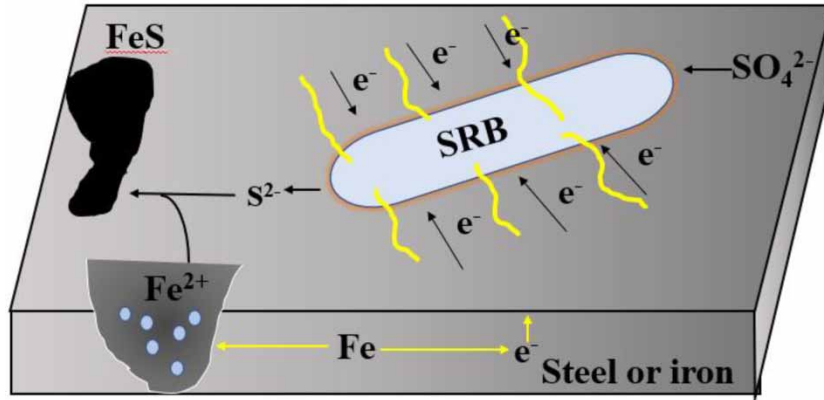


Figure 8 | The model of direct electron transfer (Chen 2015).

SO_4^{2-} in reclaimed water is an important nutrient for SRB, and its concentration can directly affect the activity of SRB (Lin 2016a). SRB is the most widely studied corrosive bacteria so far, but there are still relatively few studies on SRB in reclaimed water. In view of its widespread presence in reclaimed water, the corrosion and protection of SRB require further study.

3.1.2. Iron-oxidizing bacteria (IOB)

IOB are widespread in the environment. Various microorganisms with different physiological characteristics have evolved different forms of Fe-oxidizing ability (Emerson *et al.* 2010).

Iron oxidation by IOB produces little energy, and the rate of Fe^{2+} oxidation is much greater than that of the chemical oxidation process. Therefore, IOB will oxidize a large amount of ferrous ions during the growth, and the resulting corrosion can accelerate the decomposition of the metal and cause severe pitting corrosion (Starosvetsky *et al.* 2001, 2008). Simultaneously, the iron oxide or iron hydroxide formed by oxidation will form obvious rust tumors after precipitation and accumulation. Therefore, IOB corrosion will affect the quality of water in the pipeline and can cause serious blockages (Maeda *et al.* 1999; Ray *et al.* 2010). The corrosion mechanism diagram is shown in Figure 9. Sung *et al.* (2011) found that IOB not only causes corrosion of galvanized steel and stainless steel, but also accelerates the formation of zinc/iron precipitations. Li *et al.* (2010) found that in reclaimed water, IOB could adsorb onto the surface of carbon steel, accelerating pitting corrosion, and the corrosion potential of the system would negatively shift by 23–36%. The presence of IOB rapidly inhibited corrosion on cast iron coupons due to the formation of a passive layer in the early stage (approximately the first 20 days) and accelerated corrosion with the decrease in passive layer adhesion (Qi *et al.* 2015).

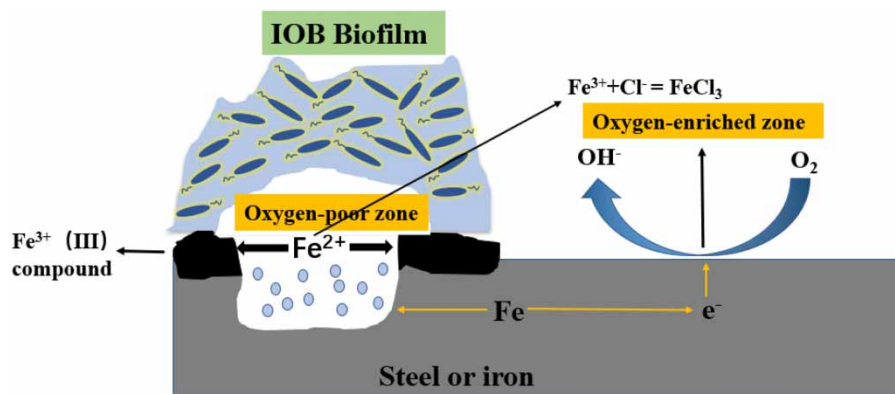


Figure 9 | The mechanism of IOB-induced corrosion.

3.1.3. Iron-reducing bacteria (IRB)

IRB are archaea or bacteria that are strictly anaerobic or facultatively anaerobic. The iron-reducing archaea mainly include Crenarchaeota and Euryarchaeota. The IRB that have been extensively studied include *Geobacter* (iron-reducing bacteria), *Geobacter* (thio-reducing bacteria), and *Shewanella* (Hedrich *et al.* 2011). Studies have

found that *Geobacteria* can obtain electrons directly from the metal surface (Mehanna *et al.* 2009; Luef *et al.* 2013), and the extracellular nanowires and cytochrome C on the outer surface play an important role in the extracellular electron transfer of *Geobacteria* (Strycharz *et al.* 2011; Snider *et al.* 2012). Early research suggested that *Shewanella oneidensis* transmits electrons to the anode through a soluble electron channel medium-riboflavin, but Pirdadian *et al.* (Pirdadian *et al.* 2014) observed that *Shewanella oneidensis* MR-1 is derived from the outer membrane and periplasm. The generated nanochannels participate in electron transfer between bacterial species.

IRB uses organic matter or H_2 as an electron donor, and Fe^{3+} as an electron acceptor to obtain energy. Because of its diversified electron transport system, IRB can drive the mineralization of organic carbon while reducing Fe^{3+} or other iron oxides and degrading aromatic organic substances such as benzene and phenol.

According to some literature, the IRB can exacerbate corrosion by increasing the concentration of corrosive iron sulfide. They explain that IRB can dissolve the corrosion-resistant metal oxide film on the metal surface and then corrode the metal (Schütz *et al.* 2013, 2015; Valencia-Cantero & Peña-Cabriaes 2014; Lovley 2017). They also suggest that Fe^{2+} is formed after IRB dissolves the metal oxide film. Fe^{2+} oxidation can block the contact of oxygen with the metal surface and hinder the progress of corrosion by consuming oxygen in the environment (Potekhina *et al.* 1999; Dubiel *et al.* 2002). The corrosion mechanism diagram is shown in Figure 10. Meanwhile, protective films such as those made of iron-phosphorus compounds may be produced on the metal surface against metal corrosion (Du *et al.* 2013). The properties of IRB that can both promote and inhibit corrosion warrant in-depth study.

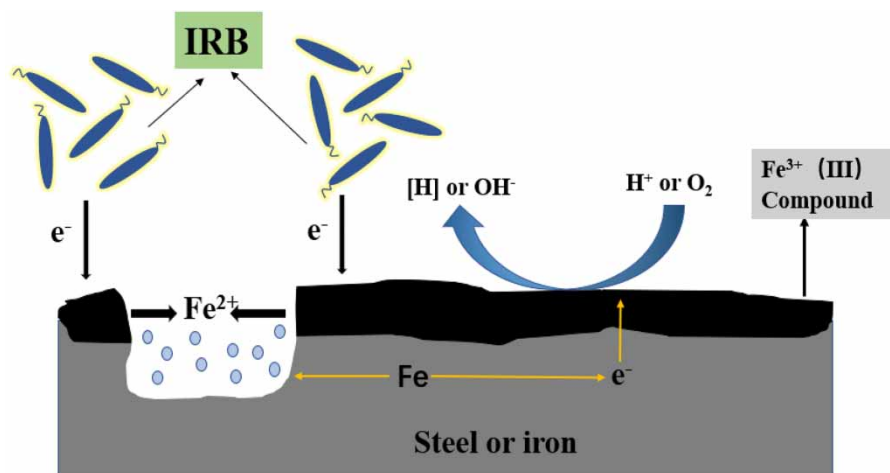


Figure 10 | The mechanism of IRB induced corrosion (Chen 2015).

3.1.4. Nitrate-reducing bacteria (NRB)

Nitrate is the most important source of nitrogen for plant growth. Nonetheless, it is also a source of environmental pollution in terms of eutrophication. The presence of nitrate in reclaimed water can promote the growth of NRB, a type of bacteria that can produce nitrate reductase, which reduces nitrate to nitrite or directly produces N_2 or NH_4^+ under the action of enzymes (Etique *et al.* 2014). Nitrite, the product of NRB, can also inhibit the growth of SRB.

Recent studies have shown that the nitrate reduction of NRB can cause microbial corrosion. Etique *et al.* (2014) found that *Klebsiella* has the ability to produce green rust in the presence of nitrate and Fe^{2+} . The corrosion mechanism diagram is shown in Figure 11. The bacteria can use organic carbon sources to convert ammonia nitrogen to nitrite and nitrate, although no enzymes related to Fe^{2+} oxidation have been found in this bacterium. Xu *et al.* (2013) found that NRB can form a biofilm. In a 1-week corrosion test, 14.5- μm deep corrosion pits could be formed on the surface of C1018 carbon steel, and the weight loss could reach 0.89 mg/cm^2 .

Like other natural environments, the surface of reclaimed water pipelines is often covered with biofilm composed of complex microbial communities, which can provide protection for the survival, growth and reproduction of microorganisms. The types of microorganisms distributed at different levels are different resulting

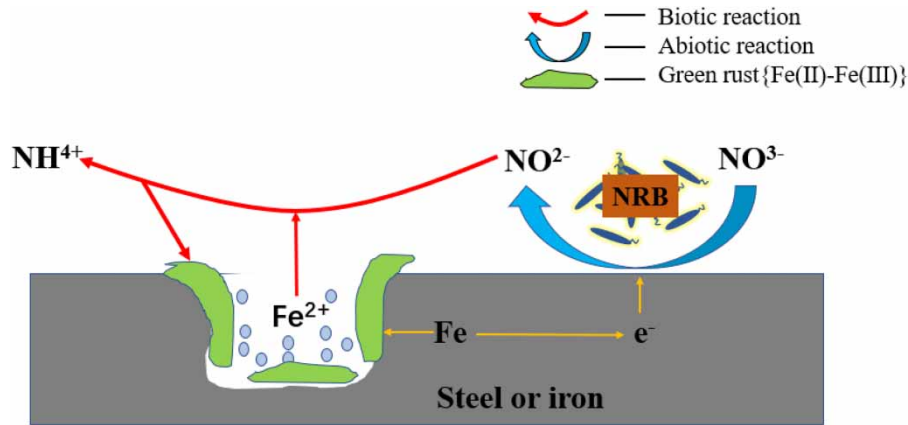


Figure 11 | The mechanism of NRB induced corrosion.

from the different concentrations of dissolved oxygen, organic matter, inorganic salts, etc. at different depths of the biofilm (Figure 12). With the development and application of various water treatment technologies, the microbial corrosion produced during the distribution and transmission of reclaimed water has drawn more attention, and the corrosion mechanism of the main microorganisms should be investigated more thoroughly.

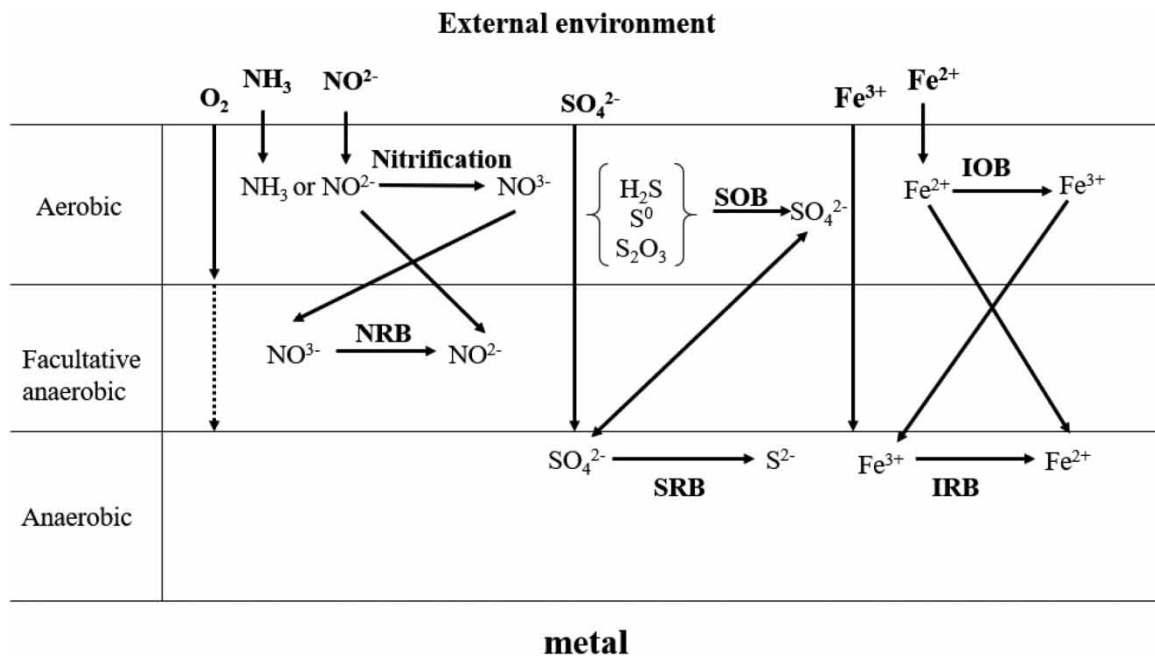


Figure 12 | Layer characteristic of typical biofilm on corroded metal surface and possible reactions in reclaimed water (Zhang & Wu 2020), (SOB-Sulfur-oxidizing bacteria).

3.2. Biofilm

Microbial corrosion is a biological–electrochemical process, which is more complicated and unique than non-biological corrosion. In addition to the general electrochemical corrosion characteristics, microbial corrosion is characterized by a unique ‘interface evolution’ process. The microorganisms constantly cycle through periods of growth, reproduction, and decay, and their life activities are involved throughout the entire corrosion process, accelerating or inhibiting corrosion. This ‘interface evolution’ not only reflects the kinetic process of metal corrosion, but also contributes to the persistence and variability of biofilms.

Biofilm is a complex mixture formed after mutual adhesion between one or more microorganisms and accumulation. It is made up of bacterial cells (algae, fungi, bacteria) and extracellular polymers (referred to as EPS), which are mainly composed of sugars, proteins and lipids; a small amount consists of nucleic acid, DNA, and

some metabolites. The microorganism itself occupies approximately 10–25% of the biofilm, and the remaining 75–90% is EPS (Costerton *et al.* 1987). EPS provides a safe place within the membrane (i.e., away from large organisms and fungicides) for the physiological activities of cell. Additionally, the presence of EPS provides the biofilm with a certain viscosity and strength for maintenance of its shape and flexibility. The biofilm can be easily removed. The formation of biofilm generally follows the four main steps shown in Figure 13.

- (1) Dissolved inorganic particles and organic matter in seawater, such as proteins, are adhered on the surface of the material to form a conditioned film;
- (2) Microorganisms in the floating state gradually ‘settle’ on the surface of the object as a result of static electricity or van der Waals forces contacting the conditioned membrane;
- (3) The attached cells continue to proliferate on the surface and secrete extracellular high polymers. Meanwhile, other microorganisms adhere to the surface, and the biofilm continues to grow and thicken until it matures;
- (4) Part of the biofilm falls off and is carried by the water flow to other places where it continues to grow, under the effects of external conditions.

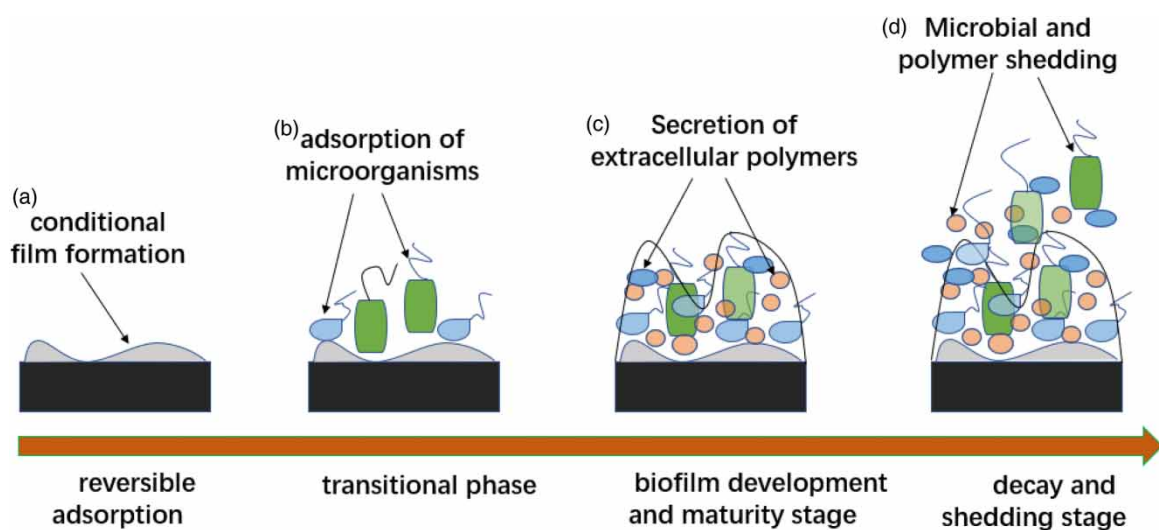


Figure 13 | Biofilm formation process (Dan *et al.* 2019).

However, there is no single specific mechanism for the process of microbial corrosion, and it is impossible to have a unified mechanism. Even the same microorganism may exhibit different corrosion behaviors for the same metal given the differences in the growth and metabolism of different microorganisms in different environments, as well as the complexity of the interaction of multiple microorganisms in the environment. Some studies have demonstrated that the existence of biofilm in reclaimed water significantly promoted corrosion (Zhang *et al.* 2015). However, it was suggested that biofilm could protect metal from corrosion by preventing the diffusion of oxygen (Zuo *et al.* 2005). Other researchers did not reach a clear conclusion but rather speculated that bacterial communities could at least promote the layering process and the formation of corrosion tubercles (Jin *et al.* 2015). In fact, several mechanisms often act together in the corrosion process, but in different ways.

4. FACTORS AFFECTING PIPELINE MICROBIAL CORROSION

Factors such as influent, reclaimed water quality, pH, disinfection methods, and the interaction between microorganisms have distinct effects on metal corrosion by microorganisms. Some of the organics and nutrients in reclaimed water can support the growth and metabolism of microorganisms, and some added disinfectants can change the growth environment to promote or inhibit the life activities of microorganisms. According to current research, the following four factors may have a relatively great influence on the microbial corrosion of reclaimed water.

4.1. Water quality conditions

The water quality conditions of reclaimed water include many aspects, and the factors affecting microorganisms are also different. Among them, four water quality parameters – COD, Fe, P, Ca^{2+} and pH are discussed below.

The effect of COD on microbial corrosion is generally considered as a carbon source for microbial growth and metabolism, which promotes the growth of microbes into colonies or biofilms, and affects the corrosion of materials after attaching to the surface of the material. A study by Bu & Hou (1996) shows that COD has a significant impact on corrosion when its concentration in the water environment is higher than 100 mg/L. As one of the main nutrient sources for microorganisms, the influence of COD on microbial corrosion is not negligible.

The presence of Fe has a specific effect on the corrosion of steel. Iron bacteria are present when the iron content of the water reaches 0.2–0.3 mg/L. Iron bacteria can convert the iron ions in water into iron hydroxide that deposits onto pipe surfaces and creates an anaerobic environment for high iron, which is conducive to the growth of SRB and accelerates the corrosion of the pipe (Li 1987).

As a nutrient element required by microorganisms, P can promote the growth and metabolism of microorganisms and help in the synthesis of extracellular polymers. Yet the presence of P also inhibits the corrosion of pipes. P-containing compounds deposited on pipe surfaces can form anions that have a selective permeability scale layer, which reduces the sensitivity of the pipe to anion corrosion (Wang *et al.* 2010).

The presence of Ca^{2+} promotes the fouling of the conveyance pipeline, and the corrosion of the pipeline network when fouling is serious. However, Ca^{2+} participates in the synthesis of microbial extracellular polymers, which increases the compactness of biofilms (Zheng & Zhang 2010), inhibits the migration of corrosive particles to the pipe surface, and reduces the corrosion sensitivity of pipes.

The pH itself can have an impact on the inorganic corrosion of the pipe. A water environment with a low pH may cause the dissolution of the protective layer on the pipe surface (Davidson *et al.* 1996) and promote the corrosion of metal materials. When the pH value of the water environment is <6 , the corrosion rate of metal materials will increase rapidly with decreases in pH (Reyes *et al.* 2008). In the presence of microorganisms, changes in pH can promote or inhibit their activity by affecting the beneficial or harmful characteristics of the environment on their growth, metabolism, and viability (Chen 2009), which thereby affects the microbial corrosion process in the environment. The effects of the various water quality parameters on microbial corrosion are summarized in Table 3.

Table 3 | Influence of water quality parameters on microbial corrosion

Water quality parameters	Effect on microorganisms	Impact
COD	As a carbon source	Promotes the formation of biofilms by microorganisms
Fe	Provides Fe element	Conducive to the growth of IRB and SRB
P	Provides P element	Promotes the formation of biofilm by microorganisms; reduces the sensitivity of pipes to anionic corrosion
Ca^{2+}	Participates in the synthesis of microbial extracellular polymers	Promotes fouling of transportation pipelines and corrosion of pipe networks; increases the density of biofilms and inhibits the migration of corrosive particles to the surface of pipes

4.2. Disinfection methods

Water quality with large variations in some chemical indicators (e.g., when disinfectants are added or iron is released in pipelines) is considered chemically unstable in the pipeline network transmission and distribution process. Disinfectants can inactivate microorganisms and indirectly affect the progress of microbial corrosion.

Chen *et al.* (2013) has observed that the use of disinfectants increases the number of bacteria in the biofilm and that the biodiversity in the membrane depends on the concentration of the disinfectant. The retention time is more beneficial to the growth of bacteria in the pipeline. However, Dan (2012) found that when the concentration of chlorine dioxide is greater than 6 mg/L, the removal of coliform bacteria can exceed 99%. This shows that the inactivation effects of disinfectants are different under complex conditions of multiple microorganisms, and this fact should be further examined. Some studies also indicate that the microbial community changed substantially after disinfection (i.e., ozone, UV irradiation, and/or chlorination) owing to the presence of different disinfectant-resistant bacteria.

4.3. Role of microorganisms

Corrosive microorganisms are often attached to the surface of reclaimed water pipeline materials and form a bio-film structure. Corrosive biofilms are typically composed of various microorganisms including bacteria, fungi, archaea, and eukaryotes. Different microorganisms have different metabolic abilities. In the natural environment, the microbial community can release various signal molecules to 'communicate' with one another, forming a synergistic or competitive metabolism and allowing the corrosive microbial community to perform functions that a single flora would be incapable of performing.

For iron pipes of different circulating water channels, [Yang et al. \(2014\)](#) found that the types and quantities of corrosion microorganisms and the types and amounts of corrosion products differed depending on the sampling point, corrosion stage, and inflow water source. [Wang et al. \(2012\)](#) discussed the morphological structure of corrosion products and the composition of corrosion microbial communities at different time periods of the iron corrosion process in the reclaimed water distribution system. In the early stage of corrosion, the synergy between the growth and metabolism of SRB/SOB and IRB/IOB, bacteria and metabolites, and biological and non-biological corrosion promotes the corrosion of metals. In the later stage of corrosion, the anaerobic IRB becomes the main functional bacteria with the formation of passive film, and biomass and bacterial diversity are reduced. IRB can prevent the diffusion of oxygen by producing Fe^{2+} through metabolization. IRB can inhibit the further occurrence of corrosion through its synergistic effect with IOB. For the role of microorganisms, artificially mixed cultures verified that the promotion of corrosion by SRB can be diminished in the presence of *Pseudomonas aeruginosa* (denitrifying bacterium) ([Batmanghelich et al. 2017](#)). Therefore, the microbial corrosion of materials is often a comprehensive effect of the microbial community.

The microbiological corrosion of reclaimed water pipeline materials may be dominated by a single factor from time to time, but is also affected by a combination of multiple factors. In the future, studies focusing on corrosion protection for reclaimed water supplies should explore the corrosion mechanism of multiple factors.

5. MITIGATION STRATEGIES FOR MICROBIAL CORROSION OF RECLAIMED WATER

An important factor affecting the growth of microorganisms is the availability of organic nutrients ([Narasimhan et al. 2005](#); [Alley 2007](#); [Ghunmi et al. 2010](#); [Ajibode et al. 2013](#)). Therefore, researchers have proposed the concept of biological stability, which refers to the potential of organic matter or nutrient substrates in water to support the growth of heterotrophic bacteria ([Peng 2009](#)). Assimilable organic carbon (AOC) is generally considered to be a reliable indicator of the biological stability in drinking water ([Jiang et al. 2011](#)). The biological stability of reclaimed water can greatly influence water quality for end users given the overall increase in the amount of reclaimed water being used, the extension in the reclaimed water pipeline, and the long retention time of reclaimed water within the pipeline. Thus, AOC is often considered as the first indicator of biological stability, informing optimization and control of the treatment process.

5.1. Coagulation

Coagulation usually promotes the transition of small particles to larger particles, and reduces the total dissolved solids content along with many other organic and inorganic components ([Thomure et al. 2014](#)). When P17 and NOX were used in reclaimed water as test strains, coagulation was found to reduce the amount of AOC in the reclaimed water to a certain extent ([Thayanukul et al. 2013](#)). In addition, the AOC content in the secondary effluent increased significantly after coagulation when using three new strains, namely ZJ2, G3, and G6, for AOC testing ([Zhao et al. 2014](#)). The coagulation process mainly helps to remove high-molecular-weight organics, resulting in an increase in AOC after coagulation. Similar results were obtained after analyzing the composition of a solidified membrane bioreactor (MBR) ([Yu et al. 2017](#)). In general, although the coagulation process can remove organic matter to a certain extent, this method alone cannot guarantee biologically stable reclaimed water. Therefore, coagulation has a certain inhibitory effect on microbial regrowth, but coagulation alone cannot completely inhibit microbial pipeline corrosion in reclaimed water.

5.2. Membrane filtration

Membrane filtration technologies mainly include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) ([Guo et al. 2012](#)). In practice, membrane-based water reuse systems normally follow a sequence of filtration steps, and dual membrane systems comprised of MF/UF and RO modules are commonly applied ([Shan et al. 2005](#)). Membrane filtration technologies have a strong filtering effect on AOC in the

reclaimed water, they can control biological stability to some extent, and help prevent microbial corrosion of the reclaimed water.

5.3. Biological filtration and adsorption

Biological filtration is considered as a cost-effective and reliable technology for the removal of organic compounds from water, as well as from waste gas streams (Iaconi 2012). For reclaimed water, current studies on ozone-BAC evaluation have mainly focused on bulk water quality parameters and trace organic contaminants (Gerrity *et al.* 2011); biological stability issues for combined systems need further evaluation. Improvements in operating conditions (e.g., longer contact time) may be required if the performance of biological filtration systems is poor (Matamoros *et al.* 2012).

5.4. Disinfection

Disinfection is a crucial and final step to ensure the microbial safety of water. The main disinfection techniques currently used include chlorination, ozone and ultraviolet irradiation.

5.4.1. Chlorine disinfection

The advantages of disinfection with chlorine are its low cost and satisfactory disinfection effect. It is particularly important for residual chlorine to be maintained in reclaimed water pipelines to achieve a continuous disinfection effect. However, the biological stability of reclaimed water after chlorine disinfection can become unstable (Cong 2017). The AOC level in chlorine disinfected tertiary effluent is higher than that of the secondary treatment effluent. Moreover, excessive chloride ions can be introduced owing to the addition of chlorine-based disinfectants, which may cause corrosion to the reclaimed water distribution pipe network (Cheng & Hu 2014).

5.4.2. Ozone disinfection

Ozone is a strong oxidant that is capable of oxidizing and decomposing glucose enzymes, destroying organelles, DNA, and RNA and inactivating bacteria. Lin and others (Lin 2016b) found that the AOC level was substantially increased when secondary effluent was further treated with ozone oxidation, resulting in a decrease in the biological stability of the water quality. Yet the composition of organic matter in water samples varies largely owing to the differences in the water quality of the influent as well as the various secondary treatment processes involved. Furthermore, although ozone has high disinfection efficiency, it lacks continuous disinfection ability during reclaimed water transport and distribution. Using ozone alone hardly guarantees the biological stability of reclaimed water, and the resulting microbial regrowth may lead to microbial corrosion of pipelines (Hulyao 2009).

5.4.3. Ultraviolet disinfection

Ultraviolet disinfection is a physical disinfection method. Ultraviolet rays of the appropriate wavelength can cause cell death and achieve the purpose of disinfection by destroying the molecular structure of DNA or RNA in the cells of microorganisms (Jianlong 2015). Ultraviolet disinfection is a fast and highly efficient disinfection method with easy operation and management, which does not affect the physical and chemical properties of water. However, it lacks continuous disinfection ability, especially under dark conditions, and the treated microorganisms can potentially undergo repair and become reactivated. Therefore, in actual practice, chlorine is often needed following ultraviolet disinfection, and a certain residual chlorine concentration must be maintained during water transport and distribution (Eric *et al.* 2007).

Disinfection is generally the last step of the water reclamation process. Careful consideration should be given to controlling the amount of disinfectant used, selecting the frequency and points of dosing and applying combined or synergistic disinfection processes to broaden the spectrum of microbial inactivation. The combined application of ultraviolet disinfection with other disinfection technologies will be important directions for development, including novel, more environmentally friendly disinfection technologies.

5.5. Pipe

The choice of pipes is key for the water transport and distribution network. Presently in China, metal pipes and plastic pipes are most commonly used for water transport. Microbial reactivation and regrowth in pipes mainly occur because of two factors. First, pipes soaking in water for an extended period may release some metal ions into the water, and nutrients can also promote the regeneration of bacteria. Therefore, corrosion of pipes should

be used as a reference factor for measuring the regeneration of bacteria in the water of the pipe network. Second, for pipes with strong corrosion resistance, the roughness and holes of the inner wall of the pipe should be taken into consideration. Physical and chemical properties such as temperature can potentially influence bacterial growth. A study has mentioned that PE pipes and PVC pipes are not conducive to the growth of biofilms compared with cast iron pipes and steel-plastic pipes (Niquette *et al.* 2010). However, other studies have indicated that regardless of the type of pipe used, a certain thickness of biofilm will be formed on the pipe wall after long-term operation, and the quality of influent, effluent, disinfectants, and the physical and chemical properties of the pipe may affect bacterial growth in the pipe network (Percival *et al.* 1998). Therefore, the proper selection of suitable pipe material and management strategies is essential. For example, for inhibition of bacterial regeneration and ensuring the quality of effluent, management strategies may include a routine period of flushing and/or pipe replacement to reduce corrosion and scaling.

Because of complex changes in the reclaimed water environment, corrosion is usually affected by various microorganisms, pipeline materials, and the conditions of the surrounding environment. Therefore, various prevention and mitigation methods should be considered and applied in an integrated manner.

6. CONCLUSIONS

With the expansion of reclaimed water use worldwide, the microbiological corrosion issues have attracted more and more attention. This paper aims to give an overview of microbial corrosion situations in reclaimed water distribution pipelines and applications and summarize the key microorganisms, corrosion mechanisms and the main affecting factors. It is identified that although cast iron pipes are used widely, their corrosion resistances are relatively weak, which calls for anti-corrosion methods or alternative pipe material. Notably, IRB, IOB, SRB and NRB are recognized as the main corrosive microorganisms. Their interactions and the formation of biofilm are complex. Besides, water matrixes including the organic and nutrient conditions and pH levels can affect the corrosion behaviors to some extent. Consequently, this paper further presents the possible control methods and suggests that future research can be directed towards innovative disinfection technologies, complex mechanisms related to biofilm formation and changes in corrosive microorganisms at the community level, and the development of new anticorrosive pipeline material.

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CONFLICT OF INTEREST

The authors declare no financial or commercial conflicts of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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