ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

Water Conservation and Management (WCM)

DOI: <http://doi.org/10.26480/wcm.02.2021.78.84>

RESEARCH ARTICLE

EFFECTS OF TEMPERATURE AND CHANGING DISINFECTANTS ON STEEL WATER PIPES CORROSION: CASE STUDY OF MASHHAD, IRAN

Mobin Rahimi-Golkhandan^a, Shahnaz Danesh^{a*}, Ali Davoodi^b

^a Department of Civil Engineering, Ferdowsi University of Mashhad, Iran

^b Department of Materials Engineering, Ferdowsi University of Mashhad, Iran

*Corresponding Author Email: sdanesh@um.ac.ir

This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

ARTICLE DETAILS

Article History:

Received 25 July 2021
Accepted 29 August 2021
Available online 02 October 2021

ABSTRACT

Water pipe corrosion inflicts big health problems and financial damages to societies. Temperature, pH, type, and dosage of oxidants, and DO are some of the key factors that affect water pipe corrosion. The aim of this research is to assess the impacts of temperature (15 and 25°C), dosage of potassium permanganate (0, 1 and 2 mg/L) and sodium hypochlorite (0, 0.5 and 1 mg/L) on corrosion of steel pipes. To measure the corrosion of steel specimens, OCP, EIS and potentiodynamic polarization tests were conducted. The results showed a direct relationship between temperature and corrosion rate. A 10-degree raise in the temperature, caused a 25% increase in corrosion current density (CCD). Adding sodium hypochlorite to the solution, decreases CCD by around 50%. Moreover, potassium permanganate proved to have a positive impact on reducing CCD by up to 21%. The results demonstrate that simultaneous usage of NaClO and KMnO₄ for water disinfection can have beneficial impact on corrosion of steel pipes. Finally, our analysis suggests that when combined with KMnO₄, lower dosage of NaClO significantly increases polarization resistance. The findings of this research highlight the impact of disinfectants on steel water pipes corrosion in different temperatures and supports water infrastructure decision-makers in more effective rehabilitation and maintenance of water pipes. Further, our results inform decision-makers for a more effective infrastructure design and resilience planning to random failures caused by corrosion.

KEYWORDS

Corrosion, disinfection, potassium permanganate, sodium hypochlorite, water treatment, water quality, steel pipes, infrastructure.

Highlights

- The impact of two disinfectants (sodium hypochlorite and potassium permanganate) under varying temperatures was investigated.
- NaClO proved to have positive impact on corrosion inhibition of ST52 steel by its strong biocidal effect.
- Applying KMnO₄ had beneficial impact on reducing the corrosion rate.
- Simultaneous usage of both NaClO and KMnO₄ was also beneficial, despite their different intrinsic characteristics (NaClO is a depolarizer or electroactive substance, while KMnO₄ is a passivator).

1. INTRODUCTION

Water is a critical infrastructure and the quality of water is key for the well-being of the society (Forde et al., 2019). Low water quality can exacerbate water scarcity (van Vliet et al., 2017) that has been intensified in many developing countries in the past decade (UNEP, 2016). Raw water, regardless of its source, requires to be treated, and if water

treatment plants face operational challenges, sustained provision of water may be interrupted. These challenges could be water treatment infrastructure aging, pipeline corrosion, poor monitoring, and maintenance issues that could jeopardize the well-being of consumers (Lee and Schwab, 2005; Ohwo, 2016).

Corrosion of water treatment plants' facilities and structures is a major concern for operators and managers. This phenomenon endangers human health, causes colossal financial damages, lowers water quality, reduces carrying capacity of pipes and leads to a faster rate of structural failure (St. Clair and Sinha, 2012; Taghipour et al., 2012; Liu and Kleiner, 2013; Beimeng et al., 2015; Jin et al., 2017; Sakran, et al., 2019; Ighalo et al., 2020). Since the seminal investigation of Larson and Skold (1958) in corrosion of metal and steel water pipes, the impact of several parameters on water pipe corrosion has been explored. Steel pipes. Several factors contribute to corrosion of steel pipes including dissolved Oxygen (DO) (Wasim et al., 2018; Shams et al., 2019), pH (Tang et al., 2018; Abbasi et al., 2020), and hydrodynamic conditions of water (Madasamy et al., 2018; Liu et al., 2020).

For instance, Sarin et al. (2004) analyzed the effect of DO on the corrosion of water pipes and concluded that when DO is present, the flowing water

Quick Response Code

Access this article online

Website:

www.watconman.org

DOI:

10.26480/wcm.02.2021.78.84

conditions cause less iron release than during stagnation. Testing the effect of DO on galvanized steel pipes, carbon steel pipes and ductile cast iron pipes, Jung et al. (2009) found that decreasing DO concentration from 9 ± 0.5 mg/L to 2 ± 0.5 mg/L decreases corrosion between 70-90% in these pipes. In water infrastructure corrosion analysis, usually different factors that might cause corrosion are investigated. For example, Zhang et al., (2021) studied the impact of several factors on manganese release in cast iron pipes. Their results showed that as pH and alkalinity decreases manganese release from corrosion scale increases. Similarly, analyzing the effect of varying temperature and alkalinities on the corrosion of galvanized steel pipes shows that higher temperature significantly increases corrosion rate while increased alkalinities enhances the protective zinc coating (Li et al., 2020).

Another parameter that can cause corrosion in water pipes is disinfectants (Li et al., 2019; Martin et al., 2020; Zhang et al., 2021). Chlorine and chlorine based biocides such as sodium hypochlorite (NaClO) have played an essential role in improving sanitation, hygiene and quality of water (Galal-Gorchev, 1996; Arnold and Colford, 2007; Assaidi et al., 2020; Powers et al., 2021). However, in several works, the effect of chlorine and chlorine based disinfectants such as sodium hypochlorite on corrosion of water pipes were reported. For instance, copper pipes release more copper ions due to an increase in chlorine concentration (Garcia-Avila et al, 2018). In contrast, in another research, the lowest copper concentration was observed at high chlorine dosage with high pH and low alkalinity (Rahman et al, 2007). Interestingly, NaClO decreases corrosion rate through eliminating microorganisms present in water samples (Su et al, 2014; Oliveira et al, 2016).

Specifically, in metal pipes, chlorine impacts corrosion in two different ways: (a) chloride ion increases iron dissolution, and (b) hypochlorous acid oxidizes ferrous (Cui, 2016). In addition, increasing chlorine concentration escalates Larson-Skold index which indicates water corrosivity (Hu et al., 2018). A Significant rise in chlorine dosage leads to increased release of metal ions including Fe and Al (Li et al., 2020). The influence of chlorine and chloramine on cast iron pipes was explored by Li et al. (2014). They concluded that chloramine causes more corrosion compared to chlorine. Likewise, Zhang et al. (2019) investigated the effect of NaClO and chlorine dioxide (ClO_2) on cast iron pipes and reported that both disinfectants cause corrosion but the impact of ClO_2 is higher than NaClO.

In addition, potassium permanganate (KMnO_4) has long been used in water treatment for oxidizing iron, manganese (Knocke et al, 1991; Khadse et al, 2015; Yu et al, 2015) and arsenic ions (Sorlini and Gialdini 2010, 2014), reducing natural organic matter and disinfection by-products formation (Hidayah and Yeh, 2018), and oxidizing pharmaceutical pollutants (Hu et al, 2011; Rodriguez-Alvarez et al, 2013; Cheng et al, 2015). KMnO_4 has been also used as a biocide to control microbial growth (Cleasby et al, 1964; Yahya et al, 2008; Naceradska et al., 2017; Gheibi et al., 2019). Similar to NaClO, corrosion inhibition performance of permanganate ion has been investigated. KMnO_4 can increase corrosion resistance of AZ91 Mg alloy (Hwang et al, 2009) and 2024 aluminium alloy coating (Yang et al, 2010). Furthermore, KMnO_4 plays a key role in reducing potential difference in Al-Co interface that decreases galvanic corrosion (Lagudu et al, 2013).

Water treatment plants might use NaClO and KMnO_4 together (Konieczny, 2008; Sorlini et al., 2010; Yu et al., 2015;). The idea behind using NaClO alongside KMnO_4 is based on the fact that NaClO and KMnO_4 are oxidizing salts with contradictory characteristics. While the former is depolarizer and corrosive, the latter is categorized as a passivator salt (Revie, 2008). Understanding the effects of these two oxidants with contrary effects on steel pipe corrosion is crucial for water treatment and infrastructure management. Despite the contrary effects of these two disinfectants on steel pipe corrosion, their impact on steel pipe corrosion when used together is largely overlooked. Different dosage of these disinfectants might have a different effect on corrosion. In addition, water temperature could contribute to the corrosion effects of these disinfectants. Thus, in this paper, we investigate the effects of type and dosage of disinfectants and temperature of water on corrosion of ST52 steel pipes. Through an

experimental design, the effects of these factors were tested on steel pipes in the main water treatment plant in Mashhad, Iran. This study will provide a better understanding of the effects of NaClO and KMnO_4 on steel pipes corrosion that could contribute in: (a) more informed water treatment planning considering the simultaneous effects of these two disinfectants, (b) more targeted monitoring, maintenance, and rehabilitation of water pipes, and (c) better design strategies for water pipes. Ultimately, the sociotechnical benefits of these contributions would be in higher quality of water and water safety, as well as higher resilience of water infrastructure to random failures caused by corrosion.

2. MATERIALS AND METHODS

2.1 Materials

The effects of NaClO, KMnO_4 , and temperature on corrosion of ST52 steel pipes was studied. All the experiments were performed on high-strength low-alloy ST52 steel and specimens were prepared as flat samples with 1×1 cm² surface area. The chemical composition of ST52 steel in weight percent is illustrated in Table 1.

Table 1: Chemical composition of ST52 steel specimens

Elements	C	Mn	P	S	Si	V	Fe
wt%	0.23	1.35	0.04	0.05	0.4	0.01	Balance

Prior to corrosion experiments, the ST52 specimens were first wet-grounded through SiC paper from 60 to 1200, then washed with alcohol and deionized water, and finally dried with air. We used experimental design to examine the impact of NaClO, KMnO_4 and temperature on the corrosion of ST52 steel. The experimental design of this research is shown Table 2. NaClO (15% available chlorine) was the product of Chloran chemical production company, Semnan, Iran, and KMnO_4 (99.55-99.65% purity) was obtained from Ana Kimia Manganese, Zanjan, Iran. Raw water was used to prepare experimental solutions. It should be noted that water used for this research was supplied from one of Mashhad's water treatment plants (pH in range between 7.9 and 8.2) and ST52 steel pipes are used in that facility for water conveyance.

Table 2: Experimental design matrix

Disinfectants	Dosage (mg/L)	Temperature (°C)
NaClO	0.5/1.0	15/25
KMnO_4	1.0/2.0	15/25
Blank Tests	0.0	15/25

2.2 Electrochemical Measurements

In this research, all electrochemical tests were conducted using Zive LAB SP1 laboratory potentiostat, an Ag/Ag-Cl electrode as the reference electrode, a platinum counter electrode and ST52 coupons as working electrodes. In addition, electrochemical cell temperature was controlled by using a bain-marie bath.

First, we monitored open circuit potential (OCP) for 30 minutes. Then, we performed electrochemical impedance spectroscopy (EIS) to measure the electrochemical impedance at different conditions. Electrochemical impedance was measured in the frequency range of 1 Hz-10 kHz with the amplitude of 10 mV peak-to-peak. Subsequently EIS Spectrum Analyzer software was employed to interpret the EIS results of charge transfer resistance and solution resistance. Finally, Potentiodynamic Polarization measurements, which involved polarization curves, were conducted with the applied potential at a constant sweep rate of 1 mV/s and in the range of -250 to +500 volts around the OCP. In the end, Tafel extrapolation was used to obtain I_{corr} and E_{corr} from the polarization curves.

3. RESULTS AND ANALYSIS

3.1 Effect of Temperature on Corrosion of ST52 Steel

The impact of temperature on corrosion of steel specimens is illustrated in Figure 1 and Table 3. Diameter of nyquist semicircle, which represents

polarization resistance is significantly larger in the 15°C curve compared to 25°C. In addition, charge transfer resistance (polarization resistance) showed a 27% larger value at 15°C temperature compared to 25°C (Table 2). This suggests that lower temperature increases polarization resistance and decreases corrosion.

Figure 1: Nyquist Plot of ST52 steel specimens in absence of oxidants

Table 3: EIS and PDP results in blank tests						
Temperature (°C)	NaClO (mg/l)	KMnO ₄ (mg/l)	R _{ct} (Ω . cm ²)	R _s (Ω . cm ²)	I _{corr} (A . cm ²)	E _{corr} (V)
15	0	0	850	221	18.46×10 ⁻⁶	-0.51
25	0	0	620	240	23.12×10 ⁻⁶	-0.66

R_{ct}: charge transfer resistance
R_s: solution resistance
I_{corr}: current
E_{corr}: potential

The potentiodynamic polarization diagram of the samples in different temperatures is shown in Figure 2. It can be seen that an increase in temperature causes a negative shift in potential (Table 3). Further, the corrosion current density at 15°C was less than the other sample at 25°C by 25%.

Figure 2: Polarization Plot of ST52 steel specimens in absence of oxidants

The reason behind the increased rate of corrosion in higher temperatures can be due to an increase in the rate of corrosion reactions (Hackerman, 1952; Volk et al, 2000; Boulay and Edwards, 2001; Sarver and Edwards, 2011, Li et al., 2020).

3.2 Effect of NaClO on Corrosion of ST52 Steel

NaClO has been used as a strong biocide for more than a century in water treatment. Our analysis of the effect of NaClO on corrosion of ST52 steel specimen revealed that larger values of this substance results in more polarization resistance (Figure 3) and less negative potential (Figure 4). In addition, we observed a major decline in corrosion current density (40-53%) and a significant rise in charge transfer resistance (Table 4). Moreover, elevated temperature (25°C) have caused more corrosion current density (CCD), despite the presence of NaClO. This change in corrosion behavior can be attributed to the impact of temperature on corrosion of steels specimen that we discussed in the previous subsection.

Figure 3: Nyquist Plot of ST52 steel specimens in presence of NaClO at different temperatures: (a) 15°C, (b) 25°C

Figure 4: Polarization Plot of ST52 steel specimens in presence of NaClO at different temperatures: (a) 15°C, (b) 25°C

Table 4: EIS and PDP results in presence of NaClO						
Temperature (°C)	NaClO (mg/l)	KMnO ₄ (mg/l)	R _{ct} (Ω . cm ²)	R _s (Ω . cm ²)	I _{corr} (A . cm ²)	E _{corr} (V)
15	0.5	0	1549	272	11.16×10 ⁻⁶	-0.59
15	1	0	2162	245	9.26×10 ⁻⁶	-0.58
25	0.5	0	1237	304	12.24×10 ⁻⁶	-0.64
25	1	0	1520	413	10.88×10 ⁻⁶	-0.63

It can be inferred that limited concentrations of NaClO can have beneficial effects on corrosion behavior of ST52 steel pipes. This phenomenon can be related to the formation of an oxide layer on steel surface which increases corrosion resistance (Su et al., 2014). Furthermore, the significant impact of NaClO on killing microorganisms and the consequent impedance of biological corrosion can be another reason for the observed change in corrosion resistance (Su et al, 2014; Oliveira et al, 2016).

3.3 Effect of KMnO₄ on Corrosion of ST52 Steel

The results of polarization resistance (Figure 5) and potential (Figure 6) tests for KMnO₄ did not show a significant change in polarization resistance and potential when the concentration of KMnO₄ increases. However, the electrochemical tests indicated a rise in charge transfer resistance (9-69%) and a decline in CCD (4-21%) in presence of KMnO₄ (Table 5) compared to the results we obtained for the effect of temperature when no oxidant was used.

Figure 5: Nyquist Plot of ST52 steel specimens in presence of KMnO_4 at different temperatures: (a) 15°C, (b) 25°C

Figure 8: Polarization Plot of ST52 steel specimens in presence of both disinfectants at different temperatures: (a) 15°C, (b) 25°C

Table 5: EIS and PDP results in presence of KMnO_4

Temperature (°C)	NaClO (mg/l)	KMnO_4 (mg/l)	R_{ct} ($\Omega \cdot \text{cm}^2$)	R_s ($\Omega \cdot \text{cm}^2$)	I_{corr} ($\text{A} \cdot \text{cm}^2$)	E_{corr} (V)
15	0	1	1085	506	17.25×10^{-6}	-0.55
15	0	2	926	460	19.86×10^{-6}	-0.55
25	0	1	1050	457	18.28×10^{-6}	-0.58
25	0	2	997	465	22.11×10^{-6}	-0.61

Table 6: EIS and PDP results in presence of both NaClO and KMnO_4

Temperature (°C)	NaClO (mg/l)	KMnO_4 (mg/l)	R_{ct} ($\Omega \cdot \text{cm}^2$)	R_s ($\Omega \cdot \text{cm}^2$)	I_{corr} ($\text{A} \cdot \text{cm}^2$)	E_{corr} (V)
15	0.5	1	1254	522	12.46×10^{-6}	-0.45
15	1	1	1142	543	11.31×10^{-6}	-0.43
15	0.5	2	1250	579	12.69×10^{-6}	-0.45
15	1	2	1134	587	13.23×10^{-6}	-0.47
25	0.5	1	1065	441	14.81×10^{-6}	-0.55
25	1	1	1133	462	14.97×10^{-6}	-0.56
25	0.5	2	1109	458	13.96×10^{-6}	-0.57
25	1	2	1118	454	15.76×10^{-6}	-0.57

Figure 6: Polarization Plot of ST52 steel specimens in presence of KMnO_4 at different temperatures: (a) 15°C, (b) 25°C

This change in charge transfer resistance and CCD can be can have different causes. The presence of manganese dioxide, that has been previously used by scholars as a corrosion inhibitor (by forming a layer on metal surface), and is produced by the reaction between KMnO_4 and water (Hwang et al, 2009; Yang et al, 2010; Lagudu et al, 2013) can cause this change. This could also be due to the inherent chemical characteristics of KMnO_4 , which are proved to have biocidal effects, aside from being a strong reliable oxidant (Cleasby et al, 1964; Yahya et al, 2008).

3.4 Effect of Combined NaClO and KMnO_4 on Corrosion of ST52 Steel

NaClO and KMnO_4 were added to the solution in the concentration range of 0.5-1 mg/L and 1-2 mg/L respectively. Figure 7 shows that increasing the concentrations of both oxidants causes less polarization resistance. Our results also show that adding more oxidant shifts the potentials in the negative direction (Figures 7-8). The results of EIS and potentiodynamic polarization tests are summarized in Table 6. The comparison of both oxidants in different temperatures reveal that in 25°C change of oxidants dosage does not change the polarization resistance significantly. However, in 15°C, lower dosage of NaClO results in greater polarization resistance.

Figure 7: Nyquist Plot of ST52 steel specimens in presence of both disinfectants at different temperatures: (a) 15°C, (b) 25°C

The results indicate that higher dosage of NaClO and KMnO_4 causes a decline in charge transfer resistance and a rise in CCD of steel specimens. As mentioned earlier, both chemicals proved to be beneficial when used separately. Furthermore, when NaClO and KMnO_4 were used in combination and in moderate concentrations, they showed good corrosion resistance results. Hence, additional usage of NaClO to the solution may decrease charge transfer resistance, that can be attributed to the production of sodium perchlorate according to the reaction below:

NaClO_4 is a strong oxidant and its impact on corrosion of metal was highlighted by in several works (e.g., Abd El Rehim et al, 1999; Hassan, 2001; Zhang et al., 2018;). Also, the presence of KOH, a corrosive substance, could be considered as another reason for the decrease in the charge transfer resistance (Pruna et al, 2007; Zeng et al, 2016).

4. DISCUSSION

The results of this study indicated the effect of NaClO, KMnO_4 , and their combination on corrosion of ST52 steel pipes. Our findings suggest that lower dosage of NaClO combined with KMnO_4 significantly increases polarization resistance compared to higher dosage of NaClO. Therefore, in order to increase the effectiveness and efficiency of water treatment and mitigate the corrosion caused by the disinfectants used in the water treatment process lower dosage of NaClO combined with KMnO_4 can be used.

Monitoring and maintenance of system components such as pipelines is crucial for the reliability of water treatment and supply (Li et al., 2014; Xu et al., 2014; Asghari et al., 2018) as well as its sustainability and resilience (Boulos, 2017). Identifying the root causes of corrosion in pipelines is key for timely and successful monitoring and maintenance plans. The analysis in this study could be useful for decision-makers of water treatment facilities in better understanding of their pipelines corrosion for more informed and targeted monitoring, maintenance, and rehabilitation plans. Such plans will ensure the water treatment reliability and water quality and could enhance the resilience of water infrastructure (Falco and Webb, 2015; Faust and Kaminsky, 2017) to random failures caused by corrosion.

Further, the results of this study could be beneficial for designing coatings for water pipelines that are more resistant to the corrosion caused by disinfectants and/or utilizing pipes with other materials. In this study our focus was on the effects of NaClO, KMnO_4 on ST52 steel corrosion. Indeed, other factors such as pH and hydrodynamic conditions of water could

contribute to the corrosion of this steel pipe. Since the pH of the water used for this research that was supplied from one of Mashhad's water treatment plants was in the range of 7.9-8.2 we excluded pH from our analysis. However, in other situations that the water pH is different, the influence of this factor along with disinfectants could be analyzed. Other factors could be also considered for a more comprehensive analysis. In addition, pipes with other materials such as cast iron and copper might have different corrosion patterns to NaClO, KMnO₄ combined. Thus, future studies should investigate the corrosion of pipes with other materials to these two oxidants which could be useful for selection of pipe materials with the least corrosion to these disinfectants.

5. CONCLUSIONS

In this study, the impacts of temperature and dosage of NaClO, KMnO₄ on ST52 steel corrosion were investigated. Our results showed that increasing the temperature from 15°C to 25°C results in a decline in charge transfer resistance, and a subsequent rise in CCD. Thus, our results confirm that corrosion rate has a direct relation with temperature. Adding of NaClO and KMnO₄ into the solution improves the corrosion behavior of steel specimens by reducing CCD and increasing charge transfer resistance. However, it did not change the polarization behavior of the specimens according to potentiodynamic polarization curves. We also observed that the combined use of NaClO and KMnO₄ provided very good corrosion resistance results when moderate dosage of both chemicals was applied at 15°C. However, when maximum dosage of both chemicals were used, charge transfer resistance decreased. This finding proves that simultaneous usage of NaClO and KMnO₄ in water disinfection can have beneficial impact on corrosion of steel pipes and equipment which are being employed abundantly in water treatment plants. Finally, our findings suggest that when combined with KMnO₄, lower dosage of NaClO significantly increases polarization resistance.

ACKNOWLEDGEMENTS

Authors are grateful for the financial support and laboratory facilities provided by the Ferdowsi University of Mashhad.

REFERENCES

- Abbasi, Z., Niazi, H., Abdolrazzaghi, M., Chen, W., & Daneshmand, M. 2020. Monitoring pH level using high-resolution microwave sensor for mitigation of stress corrosion cracking in steel pipelines. *IEEE Sensors Journal*, 20(13), 7033-7043.
- Abd El Rehim, S. S., Hassan, H. H., Ibrahim, M. A., & Amin, M. A. 1999. Perchlorate pitting corrosion of a passivated silver electrode. *Monatshefte für Chemie/Chemical Monthly*, 130(10), 1207-1216.
- Arnold, B. F., & Colford, J. M. 2007. Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis. *The American journal of tropical medicine and hygiene*, 76(2), 354-364.
- Asghari, F. B., Jaafari, J., Yousefi, M., Mohammadi, A. A., & Dehghanzadeh, R. 2018. Evaluation of water corrosion, scaling extent and heterotrophic plate count bacteria in asbestos and polyethylene pipes in drinking water distribution system. Human and ecological risk assessment: an international journal, 24(4), 1138-1149.
- Assaidi, A., Ellouali, M., Latrache, H., Zahir, H., Karoumi, A., & Mliji, E. M. 2020. Chlorine disinfection against *Legionella pneumophila* biofilms. *Journal of Water, Sanitation and Hygiene for Development*, 10(4), 885-893.
- Beimeng, Q. I., Chongwei, C., & Yixing, Y. 2015. Effects of iron bacteria on cast iron pipe corrosion and water quality in water distribution systems. *International Journal of Electrochemical Science*, 10, 545-558.
- Boulay, N., & Edwards, M. 2001. Role of temperature, chlorine, and organic matter in copper corrosion by-product release in soft water. *Water research*, 35(3), 683-690.
- Boulos, P. F. 2017. Smart water network modeling for sustainable and resilient infrastructure. *Water Resources Management*, 31(10), 3177-3188.
- Cheng, H., Song, D., Liu, H., & Qu, J. 2015. Permanganate oxidation of diclofenac: The pH-dependent reaction kinetics and a ring-opening mechanism. *Chemosphere*, 136, 297-304.
- Cleasby, J. L., Baumann, E. R., & Black, C. D. 1964. Effectiveness of potassium permanganate for disinfection. *Journal-American Water Works Association*, 56(4), 466-474.
- Cui, Y., Liu, S., Smith, K., Hu, H., Tang, F., Li, Y., & Yu, K. 2016. Stainless steel corrosion scale formed in reclaimed water: Characteristics, model for scale growth and metal element release. *Journal of Environmental Sciences*, 48, 79-91.
- Falco, G. J., & Webb, W. R. 2015. Water microgrids: The future of water infrastructure resilience. *Procedia Engineering*, 118, 50-57.
- Faust, K. M., & Kaminsky, J. A. 2017. Building water and wastewater system resilience to disaster migration: Utility perspectives. *Journal of construction engineering and management*, 143(8), 04017058.
- Forde, M., Izurieta, R., & Örmeci, B. 2019. Water and health. *Water Quality in the Americas*, 27.
- Galal-Gorchev, H. 1996. Chlorine in water disinfection. *Pure and Applied chemistry*, 68(9), 1731-1735.
- García-Ávila, F., Bonifaz-Barba, G., Donoso-Moscoco, S., Del Pino, L. F., & Ramos-Fernández, L. 2018. Dataset of copper pipes corrosion after exposure to chlorine. *Data in brief*, 19, 170-178.
- Gheibi, M., Emrani, N., Eftekhari, M., Akrami, M., Abdollahi, J., Ramezani, M., & Sedghian, A. 2019. Experimental investigation and mathematical modeling for microbial removal using potassium permanganate as an oxidant—case study: water treatment plant No. 1, Mashhad, Iran. *Environmental monitoring and assessment*, 191(3), 141.
- Hackerman, N. 1952. Effect of temperature on corrosion of metals by water. *Industrial & Engineering Chemistry*, 44(8), 1752-1755.
- Hassan, H. H. 2001. Corrosion behaviour of zinc in sodium perchlorate solutions. *Applied surface science*, 174(3-4), 201-209.
- Hidayah, E. N., & Yeh, H. H. 2018. Effect of permanganate preoxidation to natural organic matter and disinfection by-products formation potential removal. *Journal of Physics: Conference Series*, 953(1), 012218.
- Hu, J., Dong, H., Xu, Q., Ling, W., Qu, J., & Qiang, Z. 2018. Impacts of water quality on the corrosion of cast iron pipes for water distribution and proposed source water switch strategy. *Water research*, 129, 428-435.
- Hu, L., Stemig, A. M., Wammer, K. H., & Strathmann, T. J. 2011. Oxidation of antibiotics during water treatment with potassium permanganate: reaction pathways and deactivation. *Environmental science & technology*, 45(8), 3635-3642.
- Hwang, D. Y., Kim, Y. M., Park, D. Y., Yoo, B., & Shin, D. H. 2009. Corrosion resistance of oxide layers formed on AZ91 Mg alloy in KMnO₄ electrolyte by plasma electrolytic oxidation. *Electrochimica Acta*, 54(23), 5479-5485.
- Ighalo, J. O., & Adeniyi, A. G. 2020. A comprehensive review of water quality monitoring and assessment in Nigeria. *Chemosphere*, 127569.
- Jin, H., Chen, X., Zheng, Z., Ou, G., & Liu, W. 2017. Failure analysis of multiphase flow corrosion-erosion with three-way injecting water pipe. *Engineering Failure Analysis*, 73, 46-56.
- Jung, H. R., Kim, U. J., Seo, G. T., Lee, H. D., & Lee, C. S. 2009. Effect of dissolved oxygen (DO) on internal corrosion of water pipes. *Environmental Engineering Research*, 14(3), 195-199.

- Khadse, G. K., Patni, P. M., & Labhasetwar, P. K. 2015. Removal of iron and manganese from drinking water supply. *Sustainable Water Resources Management*, 1(2), 157-165.
- Knocke, W. R., Van Benschoten, J. E., Kearney, M. J., Soborski, A. W., & Reckhow, D. A. 1991. Kinetics of manganese and iron oxidation by potassium permanganate and chlorine dioxide. *Journal-American Water Works Association*, 83(6), 80-87.
- Konieczny, K. 2008. Analysis of the reliability of the water treatment plants based on membrane technologies. *Przemysł Chemiczny*, 87(5), 485-488.
- Lagudu, U. R. K., Chockalingam, A. M., Eckonomikos, L., & Babu, S. V. 2013. Role of Potassium Permanganate-Based Solutions in Controlling the Galvanic Corrosion at Al-Co Interface. *ECS Journal of Solid State Science and Technology*, 2(3), 81.
- Larson, T. E., & Skold, R. V. 1958. Laboratory studies relating mineral quality of water to corrosion of steel and cast iron. *Corrosion*, 14(6), 43-46.
- Lee, E. J., & Schwab, K. J. 2005. Deficiencies in drinking water distribution systems in developing countries. *Journal of water and health*, 3(2), 109-127.
- Li, M., Liu, Z., Chen, Y., & Korshin, G. V. 2020. Effects of varying temperatures and alkalinities on the corrosion and heavy metal release from low-lead galvanized steel. *Environmental Science and Pollution Research*, 27(2), 2412-2422.
- Li, M., Wang, Y., Liu, Z., Sha, Y., Korshin, G. V., & Chen, Y. 2020. Metal-release potential from iron corrosion scales under stagnant and active flow, and varying water quality conditions. *Water research*, 175, 115675.
- Li, R. A., McDonald, J. A., Sathasivan, A., & Khan, S. J. 2019. Disinfectant residual stability leading to disinfectant decay and by-product formation in drinking water distribution systems: a systematic review. *Water research*, 153, 335-348.
- Li, X., Wang, H., Zhang, Y., Hu, C., & Yang, M. 2014. Characterization of the bacterial communities and iron corrosion scales in drinking groundwater distribution systems with chlorine/chloramine. *International biodeterioration & biodegradation*, 96, 71-79.
- Li, Z., Zhang, B., Wang, Y., Chen, F., Taib, R., Whiffin, V., & Wang, Y. 2014. Water pipe condition assessment: a hierarchical beta process approach for sparse incident data. *Machine learning*, 95(1), 11-26.
- Liu, X., Gong, C., Zhang, L., Jin, H., & Wang, C. 2020. Numerical study of the hydrodynamic parameters influencing internal corrosion in pipelines for different elbow flow configurations. *Engineering Applications of Computational Fluid Mechanics*, 14(1), 122-135.
- Liu, Z., & Kleiner, Y. 2013. State of the art review of inspection technologies for condition assessment of water pipes. *Measurement*, 46(1), 1-15.
- Madasamy, P., Mohan, T. K., Sylvanus, A., Natarajan, E., Rani, H. P., & Velmurugan, S. 2018. Hydrodynamic effects on flow accelerated corrosion at 120° C and neutral pH conditions. *Engineering Failure Analysis*, 94, 458-468.
- Martin, R. L., Strom, O. R., Pruden, A., & Edwards, M. A. 2020. Interactive effects of copper pipe, stagnation, corrosion control, and disinfectant residual influenced reduction of legionella pneumophila during simulations of the Flint water crisis. *Pathogens*, 9(9), 730.
- Naceradska, J., Pivokonsky, M., Pivokonska, L., Baresova, M., Henderson, R. K., Zamyadi, A., & Janda, V. 2017. The impact of pre-oxidation with potassium permanganate on cyanobacterial organic matter removal by coagulation. *Water research*, 114, 42-49.
- Ohwo, O. 2016. Challenges of public water provision in Nigerian cities: a review. *Journal of Water, Sanitation and Hygiene for Development*, 6(1), 1-12.
- Oliveira, S. H., Lima, M. A. G., França, F. P., Vieira, M. R., Silva, P., & Urtiga Filho, S. L. 2016. Control of microbiological corrosion on carbon steel with sodium hypochlorite and biopolymer. *International journal of biological macromolecules*, 88, 27-35.
- Powers, J. E., McMurry, C., Gannon, S., Drolet, A., Oremo, J., Klein, L., ... & Pickering, A. J. 2021. Design, performance, and demand for a novel in-line chlorine doser to increase safe water access. *npj Clean Water*, 4(1), 1-8.
- Prună, A., Branzoi, V., & Branzoi, F. 2007. Corrosion inhibition of zinc in KOH solutions. *Advanced Materials Research*, 23, 233-236.
- Rahman, S., McDonald, B. C., & Gagnon, G. A. 2007. Impact of secondary disinfectants on copper corrosion under stagnation conditions. *Journal of Environmental Engineering*, 133(2), 180-185.
- Revie, R. W. 2008. Corrosion and corrosion control: an introduction to corrosion science and engineering. John Wiley & Sons, New Jersey, United States.
- Rodríguez-Álvarez, T., Rodil, R., Quintana, J. B., Triñanes, S., & Cela, R. 2013. Oxidation of non-steroidal anti-inflammatory drugs with aqueous permanganate. *Water research*, 47(9), 3220-3230.
- Sakran, T., Matooq, P., El-Shahawy, G., Shalaby, M., Sabry, H., & Gad, M. 2019. Monitoring water quality parameters in Egyptian tap water. *Polish Journal of Environmental Studies*, 28(4), 2815-2821.
- Sarin, P., Snoeyink, V. L., Bebee, J., Jim, K. K., Beckett, M. A., Kriven, W. M., & Clement, J. A. 2004. Iron release from corroded iron pipes in drinking water distribution systems: effect of dissolved oxygen. *Water research*, 38(5), 1259-1269.
- Sarver, E., & Edwards, M. 2011. Effects of flow, brass location, tube materials and temperature on corrosion of brass plumbing devices. *Corrosion Science*, 53(5), 1813-1824.
- Shams, D. F., Islam, S., Shi, B., Khan, W., Gunawardana, B., Saad, M., ... & Khan, G. S. 2019. Characteristics of pipe corrosion scales in untreated water distribution system and effect on water quality in Peshawar, Pakistan. *Environmental Science and Pollution Research*, 26(6), 5794-5803.
- Sorlini, S., & Gialdini, F. 2010. Conventional oxidation treatments for the removal of arsenic with chlorine dioxide, hypochlorite, potassium permanganate and monochloramine. *Water Research*, 44(19), 5653-5659.
- Sorlini, S., & Gialdini, F. 2010. Conventional oxidation treatments for the removal of arsenic with chlorine dioxide, hypochlorite, potassium permanganate and monochloramine. *Water Research*, 44(19), 5653-5659.
- Sorlini, S., & Gialdini, F. 2014. Study on arsenic removal in the drinking water treatment plant of Cremona (Italy). *Journal of Water Supply: Research and Technology—AQUA*, 63(8), 625-629.
- St. Clair, A. M., & Sinha, S. 2012. State-of-the-technology review on water pipe condition, deterioration and failure rate prediction models!. *Urban Water Journal*, 9(2), 85-112.
- Su, W., Tian, Y., & Peng, S. 2014. The influence of sodium hypochlorite biocide on the corrosion of carbon steel in reclaimed water used as circulating cooling water. *Applied surface science*, 315, 95-103.
- Taghipour, H., Shakerkhatibi, M., Pourakbar, M., & Belvasi, M. 2012. Corrosion and scaling potential in drinking water distribution system of Tabriz, northwestern Iran. *Health promotion perspectives*, 2(1), 103.
- Tang, M., Nystrom, V., Pieper, K., Parks, J., Little, B., Williams, R., & Edwards, M. 2018. The relationship between discolored water from corrosion of old iron pipe and source water conditions. *Environmental Engineering Science*, 35(9), 943-952.

- UNEP, A. 2016. A snapshot of the world's water quality: Towards a global assessment. Nairobi, United Nations Environment Programme.
- van Vliet, M. T., Flörke, M., & Wada, Y. 2017. Quality matters for water scarcity. *Nature Geoscience*, 10(11), 800-802.
- Volk, C., Dundore, E., Schiermann, J., & Lechevallier, M. 2000. Practical evaluation of iron corrosion control in a drinking water distribution system. *Water research*, 34(6), 1967-1974.
- Wasim, M., Shoaib, S., Mubarak, N. M., & Asiri, A. M. 2018. Factors influencing corrosion of metal pipes in soils. *Environmental Chemistry Letters*, 16(3), 861-879.
- Xu, Q., Liu, R., Chen, Q., & Li, R. 2014. Review on water leakage control in distribution networks and the associated environmental benefits. *Journal of Environmental Sciences*, 26(5), 955-961.
- Yahya, M. T., Landeen, L. K., Forsthoefel, N. R., Kujawa, K., & Gerba, C. P. 2008. Evaluation of potassium permanganate for inactivation of bacteriophage MS-2 in water systems. *Journal of Environmental Science & Health*, 24(8), 979-989.
- Yang, W., Jiang, B. L., Shi, H. Y., & Xian, L. Y. 2010. Effects of KMnO_4 on microstructure and corrosion resistance of microarc oxidation coatings on 2024 aluminum alloy. *Journal of Central South University of Technology*, 17(2), 223-227.
- Yu, W., Campos, L., Shi, T., Li, G., & Graham, N. 2015. Enhanced removal of manganese in organic-rich surface water by combined sodium hypochlorite and potassium permanganate during drinking water treatment. *Rsc Advances*, 5(35), 27970-27977.
- Zeng, Q., Sun, J., Emori, W., & Jiang, S. L. 2016. Corrosion behavior of thermally sprayed NiCrBSi coating on 16MnR low-alloy steel in KOH solution. *Journal of Materials Engineering and Performance*, 25(5), 1773-1780.
- Zhang, H., Tian, Y., Guo, H., Kang, M., & Song, Y. 2018. Electrochemical corrosion of cast iron pipes in reclaimed water containing disinfectant. *Int. J. Electrochem. Sci*, 13, 9069-9084.
- Zhang, H., Tian, Y., Kang, M., Chen, C., Song, Y., & Li, H. 2019. Effects of chlorination/chlorine dioxide disinfection on biofilm bacterial community and corrosion process in a reclaimed water distribution system. *Chemosphere*, 215, 62-73.
- Zhang, S., Tian, Y., Guo, Y., Shan, J., & Liu, R. 2021. Manganese release from corrosion products of cast iron pipes in drinking water distribution systems: Effect of water temperature, pH, alkalinity, SO_4^{2-} concentration and disinfectants. *Chemosphere*, 262, 127904.
- Zhang, Y., & Edwards, M. 2007. Anticipating effects of water quality changes on iron corrosion and red water. *Journal of Water Supply: Research and Technology—AQUA*, 56(1), 55-68.