# EFFICIENCY AND ECONOMY OF THE INDUSTRIAL PROCESS OF WATER TREATMENT - CASE STUDY

**PROFFESIONAL ARTICLE**

*Ajdina Suljević[1], Sabina Begić[2]✉, Indira Šestan[2], Zoran Iličković[2], Gordan Avdić[2],Amir Fazlić[3]*

**DOI: 10.51558/2232-7568.2024.17.2.29**

**RECEIVED** 2024-11-09 **ACCEPTED** 2025-03-05

[1] Bimal JSC, Bijeljinska 9, 76100 Brčko, Bosnia and Herzegovina
[2] Faculty of Technology, University of Tuzla, Urfeta Vejzagića 8, 75000 Tuzla, Bosnia and Herzegovina
[3] Faculty of Science, University of Sarajevo, Zmaja od Bosne 33-35, 75000 Sarajevo, Bosnia and Herzegovina

✉ sabina-begic@untz.ba

**ABSTRACT:**
**Water preparation for industrial use commonly involves a multi-stage approach to raw water treatment. The selection of individual treatment operations is based on various factors. Adherence to regulations and standards on water quality for a specific purpose is of key importance, as the entire treatment process should meet or exceed applicable regulatory standards. In the selected plant for the preparation of industrial water, an evaluation of the efficiency and economy of the process was carried out by comparing the results of water analysis before and after each treatment, by reviewing the justification of the location of the process units in the treatment line, and by analyzing the selected process parameters. The results of water analyzes confirmed that adequate selection and location of unit operations in the raw water treatment line can have multiple beneficial effects in meeting water quality requirements for the desired purpose.**

**KEYWORDS:** water treatment; process evaluation; industrial process; treatment operations selection

## INTRODUCTION

The role of water used in industry is diverse [1], [2], and the requirements of its quality for each individual purpose can differ significantly [3]. Industrial processes mainly rely on freshwater for water supply [4], [5]. All natural waters contain different amounts of suspended and dissolved substances, gases and microorganisms, which is caused by the type of source, as well as geological specificities of the soil and contaminants with which they come into contact in the hydrological cycle [6], [7], [8]. For the same reasons, raw water most often does not meet the quality requirements for a specific purpose in industry, and it is necessary to subject it to appropriate treatment. The main purpose of the treatment, which may include one or more different operations, is the removal of contaminants, with the ultimate goal of providing the required amount of water of the desired quality with the lowest treatment costs. All alternatives are identified and evaluated in order to select a system that achieves the required treatment at the lowest cost. The multiple effects of different operations should be considered in the broader context of water quality, given that a particular operation selected to meet the requirements of one regulation may cause compliance problems with other regulations. The circumstances are different for each facility and may be different for each individual source of water used by a facility. Due to all of the above, the selection of adequate raw water treatment operations in the industry is a complex task, and requires periodic evaluation even after the establishment of the entire treatment system.

In this paper, a comparative analysis of the quality of water, before and after individual treatment operations, intended for the supply needs of a combined boiler plant (including fire-tube and water-tube boilers) for the production of steam, working pressure 12.5 (bar) and maximum pressure 15 (bar) in a selected food industry, was performed. Additionally, selected process parameters of individual water treatment units were analyzed, all with the aim of evaluating both individual operations and the entire process of raw water treatment, from the aspect of efficiency and economy. The flow diagram of the industrial water preparation plant for steam production is shown in Figure 1.

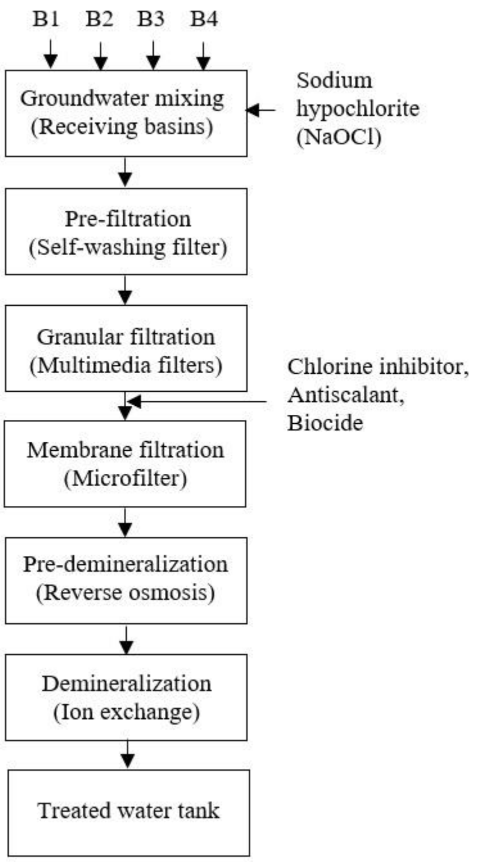


Figure 1. Flow chart of industrial water preparation for steam production

Raw water for industrial needs consists of water from four underground sources (B1, B2, B3, B4), which are fed into receiving basins and from which, as a single, mixed flow, they are subjected to appropriate treatment for supplying the steam boiler plant. Sodium hypochlorite (NaOCl) is regularly dosed into the receiving basins. The mixed flow of water from basins, before entering the multimedia filters, passes through an automatic self-cleaning filter with a pore diameter of 100 (μm). It is possible to adjust the time interval between two filter self-cleanings. The flow of water through the filter does not stop even when the filter is in the self-cleaning phase.

The multimedia filters, which make up the filter battery, are two filters filled with a combination of hydroanthracite, pyrolusite and three granulations of sand. The filtration filling of each filter is placed inside a polyethylene column with a diameter of 122 (cm) and a height of 183 (cm), coated with polyester reinforced with glass fibers. The filters are designed to work in parallel mode. The operation of each filter consists of three phases: filtration, reverse washing of the filter and rejection of the first filtrate. Iron, manganese and suspended matter are removed by means of the mentioned filters.

An oxidation-reduction potential meter is installed behind the multimedia filters, which detects the presence of residual chlorine and gives a signal to the dosing pump for dosing the sulphite-based free chlorine binding agent. In addition, antiscalant and biocide are added to the water after exiting the multimedia filter. The filtered water is further transported to a microfilter (membrane filtration), housing dimensions 1500x388 (mm) and a fineness cartridge of 5 (μm). The maximum working pressure of the filter is 10 (bar). The water flow on the cartridge is 25 ($m^3$/h), and the cartridge is changed when the pressure difference at the inlet and outlet of the filter reaches a threshold value of 1 (bar).

The outflow of water from the microfilter enters the reverse osmosis (RO) system, which consists of 14 membrane modules. The nominal flow of water entering the system is about 20 ($m^3$/h); the system works in constant mode and has a capacity of 15 ($m^3$/h) of demineralized water. Additional technical characteristics of the system are: working pH value 6.5-8, maximum chlorine concentration in the inlet water <0.1 (mg/L), maximum inlet water turbidity 1 (NTU), maximum sludge density index (SDI) value 5, maximum $SiO_2$ content 25 (mg/L), working temperature 8–30 (°C). The permeate is drained through a separate pipeline and stored in a demineralized water tank. Permeate production is 70-75 (%) of the water input to the membrane system, and its estimated flow rate is 15 $m^3$/h at 15 (˚C). The permeate tank also provides a reserve of water for occasional flushing during RO operation. The working water level in the permeate tank gives the signal to start or stop reverse osmosis. The tank is equipped with a working pump and a backup pump. The part of the water that did not pass through the membranes is drained through another pipeline. The estimated concentrate flow is about 5 ($m^3$/h). The RO system is additionally equipped with: a biocide dosing system, equipment for chemical washing of membranes, permeate, concentrate and recirculation flow meters, pressure detection sensors and an electrical conductivity meter. The RO is stopped during the backwash of the multimedia filters, and restarts after the wash is complete.

After the reverse osmosis treatment, the water enters the ion exchange (IEX) water softening system whose function is to neutralize residual hardness in the permeate. The filling of the ion exchanger consists of a strongly acidic cation-exchange resin. During the operation of the IEX system, water passes through a layer of ion-exchange resin, whereby $Ca^{2+}$ and $Mg^{2+}$ from the water are bound to the resin, and cations are released from the resin into the water, which do not affect the hardness of the water. The water flow through the ion exchange column is 22 ($m^3/h$). Considering that after passing a certain amount of water through the column, the resin is saturated and needs regeneration, the softening process works in the working and reserve column mode, i.e. while one column is working, the other is regenerating and after regeneration is in stand by mode. Tablet salt is used to regenerate the resin. Each ion exchange unit consists of a polyethylene column, coated with polyester reinforced with glass fibers, diameter 92 (cm) and height 183 (cm). The columns are interconnected by a communication cable and each is equipped with a control system. From the ion exchanger system, the water goes into the permeate tank of 20 ($m^3$) volume, and at the exit of the water from the ion exchanger there is an automatic hardness measuring device that communicates with the control system so that when the hardness value exceeds 0.3 (°dH), the ion exchanger enters the regeneration phase.

## EXPERIMENTAL

Laboratory research of water quality was conducted at:

- samples of raw water from four underground springs, marked as B1, B2, B3 and B4 and samples of their mixed flow,
- samples of the mixed flow of water after individual treatment operations in the observed industrial process.

Research methods included:

1. Laboratory quality analyzes of raw and treated water samples:

- determination of the conctent of iron (mg/L) and manganese (mg/L) by spectrophotometric method [9],
- determination of residual chlorine content (mg/L) by iodometric method [10],
- determination of pH value (dimensionless) using a pH meter [11],
- determination of electrical conductivity (µS/cm) according to the ISO 7888:1985 method [12],
- determination of total hardness (mg/L $CaCO_3$ or °dH) by titration with EDTA and eriochrome-black T as an indicator [10],

2. Direct readings of process parameters from measuring equipment in the subject water treatment process.

## RESULTS AND DISCUSSION

### THE QUALITY OF RAW WATER FROM UNDERGROUND SOURCES

The results of the analysis of individual groundwaters (Table 1) indicate the presence of a certain content of iron, manganese and the total hardness of raw water in all four sources. The industrial system can be supplied from several sources, each of which can have its own characteristics of water quality [3]. Iron and manganese are commonly found in groundwater [13], in different concentrations [14]. Although they can be in dissolved or undissolved form [15], the former is more common in groundwater due to its low redox potential. Manganese typically occurs in lower content compared to iron [16], which is confirmed by the results of the analysis of all four sources (Table 1). Iron content values in the waters of sources B2 and B3, of 0.395 and 0.399 (mg/L), are similar and slightly higher compared to those in the waters of sources B1 and B4, while the water of source B4 has the lowest values of manganese content and total hardness, i.e. 0.240 (mg/L) and 271 (mg/L $CaCO_3$). The maximum value of iron content in the analyzed raw water samples was 0.399 (mg/L), which is in accordance with the statement that groundwater generally contains iron below 5 (mg/L) [17]. The feed water quality requirements for fire-tube boilers of an operating pressure of 0.5-20 (bar) prescribe an iron concentration < 0.2 (mg/L) [18]. Suspended or dissolved iron in the feed water of the boiler by precipitation creates porous deposits of dark color (red-brown or black) on metal surfaces, which promotes the deposition of other impurities [3]. The thermal conductivity (kcal/mh°C) of iron deposits is 1-5, which compared to those of structural boiler metals, such as carbon steel (40-60) or copper (320-360), is significantly lower [19], which negatively affects the overall efficiency of the boiler, and thus the increase in fuel consumption. Taking into account the working pressure of the existing steam boiler, which is 12.5 (bar), the results of the water analysis of all four sources indicate an iron content that exceeds the mentioned requirement.

Manganese, like iron, affects the formation of deposits in boiler plants [20], and its content in feed water for low and medium pressure boilers is limited to a maximum of 0.3 (mg/L) [21]. Among the analyzed water samples, only that of underground source B4 has a manganese content of 0.24 (mg/L), which meets the aforementioned limit.

The values of the total hardness of all tested raw water samples were in the range of 271-307 (mg/L $CaCO_3$). Water with a calcium carbonate content below 60 (mg/L) is considered soft, 60-120 (mg/L) moderately hard, 120-180 (mg/L) hard, and above 180 (mg/L) very hard [22]. If the determined range of hardness of all analyzed water samples is compared with the mentioned classification, the waters of all four underground sources can be classified as very hard. Taking into account the limitation of the total hardness of boiler feed water to below 0.01 (mmol/L $CaCO_3$) [18], which is equivalent to <1.0009 (mg/L $CaCO_3$), the waters of all four underground springs do not meet the mentioned requirement for use in steam boilers, which is why their appropriate treatment is required.

Table 1. Water quality of underground sources for supplying industrial plant

| Groundwater source | Quality parameter | Value (mg/L) |
|---|---|---|
| B1 | Iron | 0.373 |
| | Manganese | 0.321 |
| | Total hardness (as $CaCO_3$) | 302 |
| B2 | Iron | 0.395 |
| | Manganese | 0.302 |
| | Total hardness (as $CaCO_3$) | 300 |
| B3 | Iron | 0.399 |
| | Manganese | 0.309 |
| | Total hardness (as $CaCO_3$) | 307 |
| B4 | Iron | 0.375 |
| | Manganese | 0.240 |
| | Total hardness (as $CaCO_3$) | 271 |

### WATER QUALITY IN THE RECEIVING BASIN

The water at the exit from the receiving basin, created by mixing of four groundwaters and designated as "mixed flow", was analyzed every 4 h for the total hardness content, pH value and residual chlorine content, and the obtained analysis results are shown in Table 2. By comparing the values of the total hardness of individual groundwaters (Table 1) with those of the mixed flow (Table 2), significant differences can be observed, i.e. lower values of the hardness of the mixed flow. Given that the dosing of the chemical agent sodium hypochlorite into the receiving basin has no effect on the total hardness of the mixed flow, the decrease in hardness can be explained by degassing $CO_2$ from the water. Namely, groundwater is typically 10 to 100 times oversaturated with $CO_2$ [23]. However, when groundwater is pumped from the source to the surface, it comes into contact with air ($O_2$) that enters the water and begins an oxidation process that releases carbon dioxide ($CO_2$) from the water into the atmosphere [24] and thus potentially causes precipitation of calcium carbonate This can result in a decrease in water hardness due to scale formation. Nevertheless, the values of total hardness given in Table 2, according to the descriptive classification of water [22], characterize the water as hard, i.e. the mixed flow of water still does not meet the requirement for the total hardness of boiler feed water of <0.01 (mmol/L $CaCO_3$) [18], i.e. <1.0009 (mg/L $CaCO_3$).

Although it is stated that for iron and manganese content up to 5 mg/L, one-stage water treatment is planned, e.g. filtration [15], this operation can be less effective for their dissolved forms, which justifies the addition of a chemical agent – sodium hypochlorite for their oxidation into insoluble forms. Taking into account the joint mixing of the waters of all four ground sources in the receiving basin, the mean values of their individual iron and manganese contents could be taken as a quality parameter of the mixed water flow. Thus, the content of iron in the mixed flow of water would be 0.3855 (mg/L) and manganese 0.293 (mg/L). However, adding NaOCl to the receiving basin reduces their content. Sodium hypochlorite acts as an oxidizing agent and in the presence of iron and manganese it can facilitate the oxidation of these metals, turning them into a form that is easier to remove from water. Depending on the pH of the water, the oxidation kinetics is more or less rapid. The results of the conducted research [25] showed that NaClO is the most effective oxidant compared to $O_2$ and $KMnO_4$ and that its addition removes 95 (%) of $Fe^{2+}$ from water at pH 9.8 in less than five minutes, while at pH 7.3 only 60 (%) of $Fe^{2+}$ is removed. The pH values from Table 2 show that the water in the receiving basin has a pH of 7.5-7.8, which is why a high degree of iron removal cannot be expected with the addition of NaOCl. In addition, manganese is more difficult to oxidize compared to iron [26], so water needs to be further treated to remove $Fe^{2+}$ and $Mn^{2+}$.

Table 2. Mixed flow quality

| Time since first sampling (h) | Total hardness (mg/L $CaCO_3$) | pH | Residual chlorine (mg/L) |
|---|---|---|---|
| 0 | 130 | 7.8 | 0.19 |
| 4 | 129 | 7.8 | 0.21 |
| 8 | 130 | 7.7 | 0.21 |
| 12 | 129 | 7.8 | 0.20 |
| 16 | 130 | 7.6 | 0.17 |
| 20 | 130 | 7.5 | 0.19 |

## WATER QUALITY AFTER MULTIMEDIA FILTRATION

Most processes for removing dissolved iron and manganese from water involve their oxidation and precipitation into insoluble compounds that are then separated by filtration [15], [24]. Rapid sand filters are often used to clean groundwater of iron and manganese [27], which justifies the choice of multimedia rapid filters in the treatment plant in question.

Before the multimedia filter, the water passes through a self-cleaning filter, which reduces the load on the multimedia filters with suspended substances. The pore diameter of the filter is 100 (μm), which indicates that it is a macrofilter, because microfiltration membranes typically have nominal pore sizes of the order of 0.1-1.0 (μm) [28]. The advantages of a self-cleaning filter for use in industrial applications, compared to alternative cartridge filters, are proven long service life and the elimination of costs and labor associated with replacement filter cartridges [29]. In the water treatment plant in question, the limit value of the pressure drop ($\Delta p$) on the self-cleaning filter is 1 (bar), while the optimal value is 0.5 (bar). Table 3 shows the values of periodic control readings of the water pressure at the inlet ($p_1$) and outlet ($p_2$) of the filter, where the results show that the pressure drop values, which are in the range 0.1-0.2 (bar), are slightly lower than the optimal value of 0.5 (bar). A moderate pressure drop is necessary to maintain an adequate water flow rate, but too little pressure drop can lead to insufficient water flow, reducing the efficiency of the filtration process.

Table 3. Pressure drop values on the self-cleaning filter

| Time since first reading (h) | $p_1$ (bar) | $p_2$ (bar) | $\Delta p$ (bar) |
|---|---|---|---|
| 0 | 3.3 | 3.2 | 0.1 |
| 8 | 3.5 | 3.2 | 0.1 |
| 16 | 3.6 | 3.4 | 0.2 |
| 24 | 3.9 | 3.7 | 0.2 |

After pre-filtration by self-cleaning filter, the water is treated with multimedia filtration, which is performed by forcing water through a column filled with appropriate filtration materials. Although in industry the filtration process can be carried out either as rapid gravity filtration or pressure filtration, the selection of pressure filtration in the water treatment plant in question is based on the fact that it enables significantly higher flow rates [30]. The selected multimedia filter is of the semicontinuous type, and ensuring continuous operation of the water treatment line is achieved by introducing two parallel-connected filtration units, whereby during the flushing of one unit the other is in operation. The use of semicontinuous operation in industrial practice is the most common [31]. Multimedia filters are those that use three or more different types of filtration media together with a supporting (non-filtering) layer of gravel at the bottom [32], [33]. Multimedia filtration is chosen because of its main advantages over mono-media and dual-media filtration: longer working time and better quality of filtered water [34], [35]. The filtration media in multimedia filters are usually arranged so that with any increase in depth, the specific density of the media particles increases while the particle size decreases [36]. This ensures that after the backwashing of the multimedia filling, the medium with the largest particle size and the smallest density stratifies at the top of the column, the one of medium size and density settles in the middle, and the heaviest but with the smallest particle diameter settles at the bottom of the column [37]. The arrangement of media layers in the considered multimedia filter is, in order from top to bottom: hydroanthracite, pyrolusite and quartz sand, which enables complementary functions of each type of media. Hydroanthracite is a form of anthracite coal that has been specially processed for use as a filter media in water treatment [38]. Its lowest density, 1.4-1.6 (g/cm$^3$), compared to the other two media, enables greater granulation of its particles in the filter, thus allowing better water flow while reducing filter clogging. In addition, it has a large surface area and a porous structure, which makes it effective for the adsorption of certain contaminants [39]. The density of pyrolusite of 4.7-5.0 (g/cm$^3$) compared to hydroanthracite enables a smaller diameter of its particles placed in the layer below. Pyrolusite primarily consists of manganese dioxide ($MnO_2$), i.e. represents its most stable form [40]. Its role is reflected in the adsorption and oxidation of dissolved iron and manganese [41], [42]. Pyrolusite acts as a catalyst that helps convert dissolved forms of iron and manganese into their insoluble forms, which are then easily filtered out. A layer of quartz sand with an average particle density of 2.65-2.75 (g/cm³) additionally purifies the water from remaining suspended matter. In fact, quartz sand in a multimedia filter for the removal of $Fe^{2+}$ and $Mn^{2+}$ from groundwater can have several functions [38], [43]: a) it contributes to depth filtration useful in capturing a wide range of particle sizes, including fine particles, b) it contributes to reactions catalytic oxidation, promoting the oxidation of iron and manganese as the water flows through the filter, c) can have a buffering effect on the pH of the water, thereby contributing to maintaining the appropriate pH range for effective removal of iron and manganese. Adsorption of manganese on the surfaces of filtration media in multimedia filters is fast [44], [45] and is accompanied by the release of $H^+$, as happens with the adsorption of cations on oxide surfaces [46], [47]. Manganese removal in granular media filters has been reported to be enhanced by the development of 'catalytic oxide layers' on the aged media, due to the formation of manganese oxide coatings [48].

In the considered water treatment plant, water analysis showed the presence of free chlorine, which indicates the possibility of oxidation of iron and manganese by chlorine [49]. Iron can be oxidized from $Fe^{2+}$ to $Fe^{3+}$ by free chlorine, however, the oxidation of $Mn^{2+}$ is relatively slow at low pH (lower than about 8 to 8.5) [50] such as that of mixed flow (table 2). However, the oxidation of manganese by free chlorine adsorbed on the oxide-coated surface is very fast (less than seconds to minutes) and can occur even at lower pH and at low temperatures [51].

Table 4 shows the results of periodic water analysis after exiting the multimedia filter. A comparison of the average values of $Fe^{2+}$ and $Mn^{2+}$ contents in each of four groundwater (Table 1) with those after water treatment with multimedia filtration (table 4) indicates the achieved degree of removal of iron up to 92.21 (%) and manganese 100 (%). In this way, the quality of the feed water for reverse osmosis is additionally improved and at the same time it protects the fine pre-filter with a pore diameter of 5 (μm) that is part of the reverse osmosis, that is, the frequency of replacing the filter cartridge is reduced. The slightly weaker effect of removing iron from water can be explained by its higher initial contents in raw water compared to manganese (Table 1). The maximum values of iron content and total hardness in boiler feed water are limited by feed water quality requirements for flue-tube steam boilers [18] and water-tube steam boilers [52], taking into account the boiler's maximum operating pressure. Based on the above, the iron content in the feed water of the combined boiler plant should be < 0.05 (mg/L), and the total hardness should be < 0.01 (mmol/L), i.e. $< 5.6\cdot10^{-4}$ (dH). A comparison of the mentioned limits with the results of water analysis after treatment with multimedia filtration shows that the iron content in the treated water meets the quality requirements of boiler feed water. In addition to the above, a complete removal of manganese was achieved, which is in accordance with the requirement of its maximum content in feed water for low and medium pressure boilers of 0.3 (mg/L) [21].

The lower value of the residual chlorine content in water after multimedia filtration (Table 4), compared to that in the mixed flow (Table 2), can be explained by a series of chemical and physical processes that take place inside the filter and in the presence of contaminants such as iron, manganese and increased total hardness.

Table 4. Results of water quality analysis after multimedia filtration

| Time since first sampling (h) | $Fe^{2+}$ (mg/L) | $Mn^{2+}$ (mg/L) | Residual chlorine (mg/L) |
|---|---|---|---|
| 0 | 0.03 | 0.00 | 0.16 |
| 4 | 0.03 | 0.00 | 0.16 |
| 8 | 0.03 | 0.00 | 0.15 |
| 12 | 0.03 | 0.00 | 0.11 |
| 16 | 0.03 | 0.00 | 0.13 |
| 20 | 0.03 | 0.00 | 0.13 |

### Water quality after reverse osmosis

Reverse osmosis is used to remove dissolved substances from water [53]. In the plant in question, water treatment by reverse osmosis precedes treatment by ion exchange. Although in practice there are also configurations of the reverse order, the chosen configuration is based on the fact that the use of RO before ion exchange (IEX) can significantly reduce the operating costs and the regeneration frequency of the IEX system [54]. According to Rehman and Ahmed [55], the advantages of the mentioned configuration are reflected in the following: a) lower osmotic pressure of reverse osmosis feed water gives lower pump pressure so that operating costs are low, b) lower chloride content and alkalinity of RO permeate, c) lower concentration of dissolved matter in RO permeate and d) lower concentration of dissolved substances in RO retentate. In order to increase the efficiency and lifetime of the reverse osmosis system, an effective pretreatment is required to minimize membrane clogging, scaling, and membrane degradation [54]. The above explains the pretreatment of water in the plant in question by dosing residual chlorine inhibitor, adding antiscalant and biocide, and microfiltration with a filter cartridge with a pore diameter of 5 (μm). Almost all reverse osmosis systems require pretreatment to reduce particle clogging [3], and the choice of microfiltration as pretreatment in the plant in question is based on the fact that it is a frequently used step before RO [56], which due to its fine porosity ensures a high and constant water quality [57].

Fouling of reverse osmosis membranes is caused by substances that may be present in the incoming water, such as: silicon dioxide, iron and humic acids. However, even typical 5 (μm) microfilters used upstream of a reverse osmosis system may not completely remove these impurities [58], which is why auxiliary chemicals (residual chlorine inhibitor, antiscalant, and biocide) are dosed into the water. Given that the microfilter itself is subject to the development of microorganisms on the surface of the membrane [59], as well as the formation of scale due to the hardness present in the water, and membrane degradation caused by chlorine, the mentioned chemical agents are added upstream of the microfilter in the plant in question. Residual chlorine is neutralized by adding a sulfite-based chemical agent, which reacts with it to form a non-harmful product. Among the common agents for chlorine inhibition, the sulphite-based one has been proven to be an ideal inhibitor [60]. Antiscalant, which is used in the case in question, prevents the formation of deposits of scale and other substances (metal oxides, silicates, etc.), thus enabling operation with hard water. In addition to the above, a biocide is used to control microorganisms that can develop in the previous stage of filtration. Table 5 shows the values of periodic control readings of water pressures at the inlet ($p_1$) and outlet ($p_2$) from the microfilter. As in the case of the self-washable mechanical filter, the limit value of the pressure drop ($\Delta p$) on the microfilter is 1 (bar), while the optimal value is 0.5 (bar). The read values of the pressure drop in the microfilter (Table 5) are slightly higher than those in the self-washable mechanical filter (Table 3), which can be explained by the lower diameter of the membrane pores of the microfilter compared to those of the self-washable filter, and thus the greater resistance to water flow. In other words, the larger the open area of the filter medium (the sum of all the areas of all the openings in the filter medium through which water can pass) for a given flow rate, the lower the water flow rate and thus the lower the pressure drop on the clean medium [29]. The read value of the pressure drop in the microfilter after 16 and 24 (h) of operation exceeds the limit value of 1 (bar), which indicates the necessary replacement of the filter cartridge, while the other values are within the specified limits.

Table 5. Pressure drop values in the microfilter

| Time since first reading (h) | $p_1$ (bar) | $p_2$ (bar) | $\Delta p$ (bar) |
|---|---|---|---|
| 0 | 3.9 | 3.7 | 0.2 |
| 8 | 3.9 | 3.6 | 0.3 |
| 16 | 2.7 | 1.2 | 1.5 |
| 24 | 2.7 | 1.1 | 1.6 |

Table 6 shows the values of the process parameters of the RO system and the electrical conductivity of the treated water (permeate) at the exit from the RO system of the industrial plant. Taking into account that the nominal flow of water entering the system is about 20 ($m^3$/h), the permeate flow rate (Table 6) is 14-15 ($m^3$/h). Data related to permeate and concentrate flow rates indicate that it is reverse osmosis with a cross flow. The selection of this configuration of the RO system in the plant in question, compared to the direct flow configuration, is based on its advantage to reduce the accumulation of impurities on the membrane surface [61]. By comparing the results of measuring the permeate flow rate and its conductivity (table 6), it can be seen that at a higher water flow rate through the membrane, its electrical conductivity was lower than that at a lower flow rate. The aforementioned can be explained by the dependence of the electrical conductivity of the permeate on the relative rates of water and salt transport through the membrane [62]. Namely, the applied pressure results in the transport of water through the RO membrane, while most of the dissolved substances are retained on the "inlet" side of the membrane [63]. The transport of dissolved matters through the RO membrane is a consequence of diffusion, it is constant and does not depend on pressure [62]. Therefore, with a higher permeate flow rate, the same amount of dissolved matters (which passes through the membrane) will be diluted by a larger amount of water (permeate) and vice versa.

Table 6. Process parameters of reverse osmosis and electrical conductivity of treated water

| Time since first reading (h) | Applied pressure (bar) | Permeate flow rate ($m^3/h$) | Concentrate flow rate ($m^3/h$) | Electrical conductivity (μS/cm) |
|---|---|---|---|---|
| 0 | 8.1 | 15 | 6.2 | 31.3 |
| 8 | 8.1 | 15 | 6.2 | 31.8 |
| 16 | 8.1 | 14 | 6.9 | 32.8 |
| 24 | 8.1 | 14 | 6.2 | 36.6 |

In other words, as the inlet water flux increases, the concentration of dissolved matters in the permeate decreases and the efficiency of their removal from water increases [3], which is consistent with the results in Table 6.

## WATER QUALITY AFTER ION EXCHANGE

The chosen sequence of water treatment in the considered water treatment plant, in such a way that the ion exchange operation is performed after and not before reverse osmosis, is based on the following [55]: reverse osmosis is the best method for water with higher conductivity levels; ion exchange is best for water with low conductivity; the mentioned configuration results in a small amount of wastewater from the ion exchange unit. In the considered ion exchange operation, a strong acid cation exchange resin (Na-based) is used. Na-based ion exchange resin is used more often than H-based resin to reduce the total hardness of water. Namely, sodium ions are easily regenerated from the resin during the regeneration phase of the ion exchange process, and considering that NaCl salt solution is used as a regeneration agent [64], the procedure is low-cost. If H+-based ion exchange resins were used, the regeneration process would be more complex, requiring the use of strong acids (HCl, $H_2SO_4$). In addition to the above, sodium ions are neutral and their exchange does not lead to acidity or alkalinity of the water, while hydrogen ions can contribute to the creation of excess acidity in the treated water, potentially lowering its pH.

Table 7 shows the results of the periodic analysis of the treated water at the exit from the strong acid cation exchanger. The results of the analysis of the quality of the mixed flow (Table 2) showed that the pH of the water is in the range of 7.5-7.8, while the pH range of the water after the ion exchange treatment is 6.5-6.7. The cause of the drop in the pH value of the water can be attributed to the reverse osmosis operation that preceded the ion exchange, i.e. its potential to remove minerals. The removal of minerals means that there are more free hydrogen ions in the water than before, which lowers the pH level from 6-8 to 5-7 and makes the water more acidic.

Comparison of the electrical conductivity of water after ion exchange (Table 7), whose values are in the range 0.13-0.16 (μS/cm), with those after reverse osmosis (Table 6), which were in the range 31.3-36.6 (μS/cm), indicates that by the ion exchange process a significant degree of removal of ionic species was achieved. A decrease in the electrical conductivity of water after ion exchange was also reported in other water treatment studies [65]. Water softening operation by cation exchange can remove almost all calcium and magnesium from water, and can also remove iron [66]. This is confirmed by the analysis of the total hardness of the water after ion exchange treatment in the considered industrial plant, which is 0.00 (mg/L $CaCO_3$). The obtained results of the water hardness analysis meet the quality requirement of boiler feed water of < 0.01 (mmol/L) [18], which is equivalent to 1.0009 (mg/L $CaCO_3$). Considering that the total hardness of the water has a certain correlation with its electrical conductivity [67], [68], it can be assumed that the total hardness of the water after the reverse osmosis treatment was above the limit for the quality of the boiler feed water [18], which is why the treatment of water by both reverse osmosis and ion exchange was necessary.

Table 7. Results of water quality analysis after ion exchange

| Time since first sampling (h) | Total hardness (mg/L $CaCO_3$) | pH | Electrical conductivity (μS/cm) |
|---|---|---|---|
| 0 | 0.00 | 6.7 | 0.16 |
| 4 | 0.00 | 6.7 | 0.16 |
| 8 | 0.00 | 6.6 | 0.15 |
| 12 | 0.00 | 6.7 | 0.11 |
| 16 | 0.00 | 6.5 | 0.13 |
| 20 | 0.00 | 6.7 | 0.13 |

In that way, it is possible to completely remove the total hardness which was in the range of 129-130 (mg/L) in the receiving basin (Table 2).

## CONCLUSION

Given that different types of water sources have specific characteristics in certain parameters of their quality, the type of source has an influence on the selection of treatment operations. Also, in order to select appropriate treatment operations, it is necessary to compare the quality of raw water and its desired quality for final use. In addition, the availability and cost of water treatment equipment and chemicals, maintenance services and training of operating personnel, as well as waste disposal requirements greatly influence the choice of treatment operations. In this paper, a comparative analysis of water quality before and after individual treatment operations was performed, for the supply needs of a combined boiler plant for steam production, working pressure 12.5 (bar) in the selected food industry. Individual water treatment units and their selected process parameters were additionally analyzed, all with the aim of evaluating both unit operations and the entire process of raw water treatment, from the aspect of efficiency and economy. In raw water samples from four underground sources used to supply the boiler plant, deviations from the requirements of the maximum iron content in boiler feed water were found, with the range of $Fe^{2+}$ content in the samples being 0.373-0.399 (mg/L). Among the analyzed samples, only one groundwater had a manganese content of 0.24 (mg/L) that meets the prescribed maximum limit for low and medium pressure boilers, while the others had excessive values 0.321, 0.302 and 0.309 (mg/L). The determined content of total hardness in all four groundwaters was significantly above the prescribed level, with the decreasing order of their values (mg/L $CaCO_3$) being: 307, 302, 300 and 271. Although natural aeration of water, i.e. contact with air and the consequent degassing of carbon dioxide can partially reduce its overall hardness, the overall effect on water hardness is limited and temporary. The addition of a chemical oxidant, such as sodium hypochlorite (NaClO) to water before its filtration contributes to the oxidation of dissolved iron and manganese and their easier precipitation and separation with a granular filtration medium. Multi-media filters offer improved particle and solute removal efficiency, where each individual filtration media targets specific impurities, including iron and manganese. Analyzes of water quality after the mixing of four underground waters and its treatment with multimedia sand filtration showed a decrease in the content of iron and manganese to 0.03 (mg/L) and (0.00 mg/L), which met the requirements of their maximum content in boiler feed water. In addition to the above, a reduction of the residual chlorine content was achieved, from the initial range of 0.17-0.21 (mg/L) in the mixed groundwater, to the range of 0.11-0.16 (mg/L) after its multimedia filtration. Properly selected industrial processes and their place in the overall raw water treatment line can have multiple beneficial effects on meeting water quality requirements for a specific purpose. The sequence of water treatment after multimedia filtration, in such a way as to first carry out reverse osmosis and then ion exchange, resulted in the complete removal of the total hardness of the water, i.e. from the range of 129 – 130 (mg/L $CaCO_3$) after groundwater mixing to 0.00 (mg/L $CaCO_3$) at the exit from the ion exchange column, which satisfies one of the most important requirements for boiler feed water quality. The efficiency of the selected configuration in removing ions that contribute to water hardness is also confirmed by the results of the electrical conductivity of water, which after reverse osmosis treatment had a range of 31.3-36.6 (μS/cm), and after ion exchange 0.11-0.16 (μS/cm). In addition to the appropriate selection of individual treatment operations and their place in the overall process of industrial water preparation, pre-filtration is a key operation in water treatment processes, especially when multimedia filters and reverse osmosis systems are used. By removing larger particles before the water enters the multimedia filter, pre-filtration allows them to work more efficiently, because a finer filtration medium can more effectively remove smaller particles and dissolved impurities when it is not loaded with larger fractions. Pre-filtration also helps prevent clogging or damage to sensitive equipment, such as membranes in reverse osmosis systems, allowing for high equipment performance and reduced maintenance costs.

## REFERENCES


1. M. F. Hossain, "Water," in *Sustainable Design and Build: Building, Energy, Roads, Bridges, Water and Sewer Systems*, Butterworth-Heinemann, 2019, pp. 301-418.
2. D. P. Dupont and S. Renzetti, "The Role of Water in Manufacturing," *Environmental and Resource Economics*, vol. 18, no. 4, pp. 411-432, 2001.[Online]. Available: http://dx.doi.org/10.1023/A:1011117319932. [Accessed: 11-Sep-2024]
3. S. Begić, R. Cvrk, and M. H. Stanić, *Postupci pripreme vode za industriju*. Tuzla, Bosnia and Herzegovina: In Scan Ltd., 2022.
4. H. Ritchie and M. Roser, "Water Use and Stress," *Our World in Data*, 2018. [Online]. Available: https://ourworldindata.org/water-use-stress. [Accessed: 13-Sep-2024].
5. W. Musie and G. Gonfa, "Fresh water resource, scarcity, water salinity challenges and possible remedies: A review," *Heliyon*, vol. 9, no. 8, article e18685, 2023. [Online]. Available: https://doi.org/10.1016/j.heliyon.2023.e18685. [Accessed: 13-Sep-2024].
6. P. Vasistha and R. Ganguly, "Water quality assessment of natural lakes and its importance: An overview," *Materials Today: Proceedings*, vol. 32, pt. 4, pp. 544-552, 2020. [Online]. Available: https://doi.org/10.1016/j.matpr.2020.02.092. [Accessed: Sep. 18, 2024].

7. D. Nelson, "Natural variations in the composition of groundwater," *Drinking Water Program*, presented at Groundwater Foundation annual meeting, Springfield, Oregon, USA, Oregon Department of Human Services, 2002. [Online]. Available: https://www.oregon.gov/oha/ph/HealthyEnvironments/DrinkingWater/SourceWater/Documents/gw/chem.pdf. [Accessed: Sep. 18, 2024].
8. J. I. Drever, *The Geochemistry of Natural Water: Surface and Groundwater Environments*, 3rd ed. Upper Saddle River, NJ, USA: Prentice Hall, 1997.
9. V. Stuhli, M. Zohorović, Lj. Bojanović, A. Đozić, and F. Andrejaš, *Eksperimentalne vježbe sa teoretskim osnovama iz inženjerstva zaštite okoline*, Scan Ltd., Tuzla, 2021.
10. American Public Health Association (APHA), R. Baird, A. D. Eaton, E. W. Rice, and L. Bridgewater, *Standard Methods for the Examination of Water and Wastewater*, 23rd ed. Washington, D.C., USA: American Public Health Association, 2017.
11. British Standards Institution**,** *BS EN ISO 10523:2012 - Water quality — Determination of pH*. 2012.
12. International Organization for Standardization, *ISO 7888:1985 - Water Quality — Determination of Electrical Conductivity*. Geneva, Switzerland: ISO, 1985.
13. N. Manav Demir, "Experimental Study of Factors that Affect Iron and Manganese Removal in Slow Sand Filters and Identification of Responsible Microbial Species," *Polish Journal of Environmental Studies*, vol. 25, no. 4, pp. 1453-1465, 2016. [Online]. Available: https://doi.org/10.15244/pjoes/62679. [Accessed: 13-Sep-2024].
14. H. Khozyem, A. Hamdan, A. A. Tantawy, A. Emam, and E. Elbadry, "Distribution and origin of iron and manganese in groundwater: Case study, Balat-Teneida area, El-Dakhla Basin, Egypt," *Arabian J. Geosci.*, vol. 12, no. 523, 2019. [Online]. Available: https://doi.org/10.1007/s12517-019-4689-1. [Accessed: Aug. 12, 2024].
15. D. Barloková and J. Ilavský, "Removal of iron and manganese from water using filtration by natural materials," *Polish J. of Environ. Stud.*, vol. 19, no. 6, pp. 1117-1122, 2010. [Online]. Available: https://www.pjoes.com/Removal-of-Iron-and-Manganese-from-Water-r-nUsing-Filtration-by-Natural-Materials,88490,0,2.html. [Accessed: Jun. 29, 2023].
16. Araby, R.E.; Hawash, S.; Diwani, G.E. Treatment of iron and manganese in simulated groundwater via ozone technology. Desalination 2009, 249, 1345–1349. [Online]. Available: https://doi.org/10.1016/j.desal.2009.05.006. [Accessed: Aug. 12, 2024].
17. G. Singh, „*Water Supply and Sanitary Engineering*", 5th ed. Delhi: Standard Publisher Distributors, 1999.
18. Viessmann, *"Kvalitet vode u postrojenjima parnih kotlova,"* 2008. [Online]. Available: https://www.scribd.com/document/105600917/Kvalitet-Vode-Parni-Kotlovi-Srpski. [Accessed: Jun. 26, 2024].
19. *Kurita Handbook of Water Treatment, 2nd ed*. Tokyo: Kurita Water Industries Ltd., 1999. [Online]. Available: https://www.abpsoil.com/images/Books/kurita-handbook-water-treatment.pdf. Accessed: Sep. 18, 2024.
20. Suez, *Industrial Boiler Feedwater - How to Improve Boiler Efficiency and Reduce Operating Costs*, White paper, Sep. 2021. [Online]. Available: https://purite.com/wp-content/uploads/2021/10/SUEZ-Industrial-Campaign-Boiler-Feed-White-Paper-September-2021-v1.3-High.pdf. [Accessed: Jun. 3, 2024].
21. M. S. Jami, M. K. Amosa, M. F. R. Alkhatib, D. N. Jimat, and S. A. Muyibi, "Boiler-feed and process water reclamation from biotreated palm oil mill effluent (BPOME): A developmental review," *Chem. Biochem. Eng. Q.*, vol. 27, no. 4, pp. 477–489, 2013. [Online]. Available: https://core.ac.uk/download/pdf/18622178.pdf. [Accessed: Sep. 5, 2024].
22. W. McGowan, *Water Processing: Residential, Commercial, Light-Industrial*, 3rd ed. Lisle, IL, USA: Water Quality Association, 2000.
23. M. I. Mahmud, S. Sultana, M. A. Hasan, and K. M. Ahmed, "Variations in hydrostratigraphy and groundwater quality between major geomorphic units of the Western Ganges Delta plain, SW Bangladesh," *Applied Water Science*, vol. 7, no. 6, pp. 2919–2932, 2017. [Online]. Available: https://doi.org/10.1007/s13201-017-0581-x. [Accessed: Jul. 10, 2024].
24. M. Ahmad, "Iron and Manganese removal from groundwater - Geochemical modeling of the Vyredox method," M.S. thesis, Department of Geosciences, University of Oslo, Oslo, Norway, 2012. [Online]. Available: https://core.ac.uk/download/pdf/30826276.pdf. [Accessed: Jul. 12, 2024].
25. M. F. Mamadou, M. S. F., E. H. Moussa D., O. T. A., A. M. F., and G. D. M. C., "Iron in Water: Study of Iron Removal Kinetics in Chemically Reconstituted Waters: Application to Groundwater of South Pout (PS2 Site)," *Open Journal of Metal*, vol. 11, pp. 1-10, 2021. [Online]. Available: https://doi.org/10.4236/ojmetal.2021.111001. [Accessed: May. 29, 2024].
26. H. Yang, X. Tang, X. Luo, G. Li, H. Liang, and S. Snyder, "Oxidants-assisted sand filter to enhance the simultaneous removals of manganese, iron and ammonia from groundwater: Formation of active MnOx and involved mechanisms," *Journal of*

*Hazardous Materials*, vol. 415, p. 125707, 2021. [Online]. Available: https://doi.org/10.1016/j.jhazmat.2021.125707. [Accessed: Jul. 2, 2024].

27. H. Andersson and J. Johansson, "Iron removal from groundwater in Rakai District, Uganda: a minor field study," M.S. thesis, Lulea Univ. of Technol., Uganda, 2002, Master's Thesis 2002:292CIV. [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-54321. [Accessed: Jun. 25, 2024].
28. C. Charcosset, "Microfiltration," in *Membrane Processes in Biotechnology and Pharmaceutics*, C. Charcosset, Ed. Amsterdam, Netherlands: Elsevier, 2012, pp. 101-141. [Online]. Available: https://www.perlego.com/book/1834053/membrane-processes-in-biotechnology-and-pharmaceutics. [Accessed: Aug. 6, 2024].
29. M. N. Alhands, "Removing solids with automatic self-cleaning filters," in *Proc. 15th Annu. Produced Water Seminar*, Houston, TX, USA, Jan. 19-21, 2005. [Online]. Available: https://www.environmental-expert.com/articles/removing-solids-with-automatic-self-cleaning-filters-6010/full-article. [Accessed: Jul. 14, 2023].
30. N. F. Gray, *Water Technology*, 3rd ed. London, UK: IWA Publishing, 2010.
31. Metcalf & Eddy, Inc. an AECOM Company, T. Asano, F. Burton, and H. Leverenz, "Removal of residual particulate matter," in *Water Reuse: Issues, Technologies, and Applications*, M. Wright and D. C. D. H. C. Eds., New York, NY, USA: McGraw-Hill, 2007. 373-460.
32. M. L. Gulhane and A. U. Charpe, "Domestic wastewater treatment using multimedia filter technology," *Int. J. for Scientific Research & Development*, vol. 3, no. 01, pp. 1119-1121, 2015. [Online]. Available: https://www.academia.edu/22380344/Domestic_Wastewater_Treatment_using_Multimedia_Filter_Technology. [Accessed: Sep. 2, 2023].
33. V. Anusuya, R. Malathi, P. S. Kumar, and S. S. Barath, "Characteristic study on domestic wastewater by natural absorbents using multi-media filters technology," *Int. J. Engineering Research and Modern Education*, Special Issue, Apr. 2017, pp. 39-42. [Online]. Available: https://doi.org/10.5281/zenodo.570093. [Accessed: Jun. 12, 2023].
34. N. B. Kazemi Noredinvand, A. Takdastan, and R. Jalilzadeh Yengejeh, "Removal of organic matter from drinking water by single and dual media filtration: A comparative pilot study," *Desalination Water Treat.*, vol. 57, no. 44, pp. 20792–20799, 2016. [Online]. Available: https://doi.org/10.1080/19443994.2015.1110718. [Accessed: Jan. 9, 2024].
35. M. A. Al-Ghouti, M. A. Al-Kaabi, M. Y. Ashfaq, and D. A. Da'na, "Produced water characteristics, treatment and reuse: A review," *Journal of Water Process Engineering*, vol. 28, pp. 222-239, 2019. [Online]. Available: https://doi.org/10.1016/j.jwpe.2019.02.001. [Accessed: Jul. 5, 2023].
36. N. B. Kazemi Noredinvand, A. Takdastan, R. Jalilzadeh Yengejeh, and F. Ghanbari, "The efficiency of multi-media filtration in drinking water treatment plants for the removal of natural organic matter," *J. Adv. Environ. Health Res.*, vol. 9, no. 2, pp. 117–128, 2021. [Online]. Available: https://doi.org/10.22102/jaehr.2021.277080.1215. [Accessed: Jan. 10, 2024].
37. K. V. Bhoyar, N. V. Rekkawar, and H. D. Mishra, "Analysis and design of media filter for waste water treatment," *Int. J. Innovations in Engineering and Science*, vol. 4, no. 4, pp. 73-79, 2019. [Online]. Available: https://www.ijies.net/finial-docs/finial-pdf/1204194419.pdf. [Accessed: Jul. 5, 2023].
38. American Water Works Association, *Water Quality and Treatment: A Handbook on Drinking Water*, 6th ed. New York, NY, USA: McGraw-Hill, 2010.
39. D. W. Hendricks, *Water Treatment Unit Processes: Physical and Chemical*. Boca Raton, FL, USA: CRC Press, 2006.
40. J. Jeż-Walkowiak, M. Komorowska-Kaufman, Z. Dymaczewski, M. M. Sozański, and P. Zakrzewski, "Properties of catalyst for iron and manganese oxidation in filter materials," *E3S Web Conf.*, vol. 59, p. 00014, 2018. [Online]. Available: https://doi.org/10.1051/e3sconf/20185900014. [Accessed: Oct. 3, 2023].
41. M. M. Michel, M. Azizi, D. Mirosław-Świątek, L. Reczek, B. Cieniek, and E. Sočo, "Significance of MnO2 Type and Solution Parameters in Manganese Removal from Water Solution," *International Journal of Molecular Sciences*, vol. 24, no. 5, p. 4448, 2023. [Online]. Available: https://doi.org/10.3390/ijms24054448. [Accessed: Oct. 3, 2023].
42. S. Pervez and G. S. Pandey, "Dissolved iron in ground water: Applications of lepidocrocite and pyrolusite for its removal," *Journal of Indian Water Works Association*, vol. 3, pp. 245-247, 1993. [Online]. Available: https://www.researchgate.net/publication/274835483_Dissolved_iron_in_ground_water_Applications_of_lepidocrocite_and_pyrolusite_for_its_removal. [Accessed: Oct. 3, 2023].
43. K. J. Howe, D. W. Hand, J. C. Crittenden, R. R. Trussell, and G. Tchobanoglous, *Principles of Water Treatment*. Hoboken, NJ, USA: John Wiley & Sons, 2012.
44. A. A. Islam, J. E. Goodwill, R. Bouchard, J. Tobiason, and W. Knocke, "Characterization of filter media

MnOx (s) surfaces and Mn removal capability," *J. Am. Water Works Assoc.*, vol. 102, no. 9, pp. 71–83, 2010. [Online]. Available: https://doi.org/10.1002/j.1551-8833.2010.tb10188.x. [Accessed: Sep. 11, 2023].

45. P. Hu, Y. Hsieh, J. Chen, and C. Chang, "Adsorption of divalent manganese ion on manganese-coated sand," *J. Water Supply: Research and Technology-Aqua*, vol. 53, no. 3, pp. 151–158, 2004. [Online]. Available: https://doi.org/10.2166/aqua.2004.0013. [Accessed: Sep. 7, 2023].
46. J. J. Morgan and W. Stumm, "Colloid-chemical properties of manganese dioxide," *J. Colloid Interface Sci.*, vol. 19, no. 4, pp. 347–359, 1964. [Online]. Available: https://doi.org/10.1016/0095-8522(64)90036-4. [Accessed: Apr. 10, 2024].
47. J. W. Murray, "The interaction of metal ions at the manganese dioxide-solution interface," *Geochimica et Cosmochimica Acta*, vol. 39, no. 4, pp. 505–519, 1975. [Online]. Available: https://doi.org/10.1016/0016-7037(75)90103-9. [Accessed: Apr. 11, 2024].
48. D. M. Sahabi, M. Takeda, I. Suzuki, and J.-I. Koizumi, "Removal of $Mn^{2+}$ from water by ‘aged’ biofilter media: The role of catalytic oxides layers," *J. Biosci. Bioeng.*, vol. 107, no. 2, pp. 151–157, 2009. [Online]. Available: https://doi.org/10.1016/j.jbiosc.2008.10.013. [Accessed: May 6, 2024].
49. M. Elsheikh, H. Guirguis, and A. Fathy, "A comparative study of methods used for Fe and Mn oxidation and removal from groundwater," *J. Engineering and Applied Science*, vol. 63, no. 4, pp. 277–292, 2016. [Online]. Available: https://www.researchgate.net/publication/326990940_A_comparative_study_of_methods_used_for_fe_and_mn_oxidation_and_removal_from_groundwater. [Accessed: Sep. 1, 2023].
50. W. R. Knocke, R. C. Hoehn, and R. L. Sinsabaugh, "Using alternative oxidants to remove dissolved manganese from waters laden with organics," *J. Amer. Water Works Assoc.*, vol. 79, no. 3, pp. 75–79, 1987. [Online]. Available: https://awwa.onlinelibrary.wiley.com/doi/10.1002/j.1551-8833.1987.tb02818.x. [Accessed: Jan. 16, 2024].
51. W. R. Knocke, S. C. Occiano, and R. Hungate, "Removal of soluble manganese by oxide-coated filter media: Sorption rate and removal mechanism issues," *J. Amer. Water Works Assoc.*, vol. 83, no. 8, pp. 64–69, 1991. [Online]. Available: https://www.jstor.org/stable/41293529. [Accessed: Feb. 16, 2024].
52. BS EN 12952-12:2003, "Water-tube boilers and auxiliary installations - Requirements for boiler feedwater and boiler water quality," British Standards Institution, 2003. [Online]. Available: https://img.antpedia.com/standard/files/pdfs_ora/20221211/bs/BS%20EN%2012952-12-2003.pdf. [Accessed: Jan. 16, 2024].
53. J. C. Van der Linde, E. Fosso-Kankeu, G. Gericke, N. Lemmer, and F. Waanders, *"Removal of Total Hardness and Alkalinity from RO – Reject Water,"* in *Proc. 9th Int'l Conf. on Advances in Science, Engineering, Technology & Waste Management (ASETWM-17)*, Parys, South Africa, Nov. 27-28, 2017. [Online]. Available: https://www.researchgate.net/publication/321490462_Removal_of_Total_Hardness_and_Alkalinity_from_RO_-_reject_water. [Accessed: Jun. 10, 2024].
54. Dupont**,** *FilmTec™ Reverse Osmosis Membranes Technical Manual* (Form No. 45-D01504-en). 2023. [Online]. Available: https://www.dupont.com/content/dam/dupont/amer/us/en/watersolutions/public/documents/en/RO-NF-FilmTec-Manual-45-D01504-en.pdf. [Accessed: Aug. 28, 2023].
55. H. A. Rehman and K. Ahmed, "Reverse Osmosis and Ion-Exchange Water Treatment for Boilers—A Brief Review," *Sci. Int. (Lahore)*, vol. 27, no. 6, pp. 6147–6151, 2015. [Online]. Available: http://www.sci-int.com/pdf/636372723526902857.pdf. [Accessed: May 7, 2024].
56. V. Bonnelye, L. Guey, and J. Del Castillo, "UF/MF as RO pre-treatment: the real benefit," *Desalination*, vol. 222, no. 1-3, pp. 59-65, 2008. [Online]. Available: https://doi.org/10.1016/j.desal.2007.01.129. [Accessed: Jul. 25, 2023].
57. P. Kajitvichyanukul, N. K. Shammas, Y. Hung, L. K. Wang, and J. Ananpattarachai, *Membrane and Desalination Technologies*. New York: Springer, 2011.
58. G. K. Dhawan, *Solutions to Membrane Fouling*. 1985. [Online]. Available: https://www.appliedmembranes.com/solutions-to-membrane-fouling.html. [Accessed: Aug. 18, 2023].
59. J. Kacprzyńska-Gołacka, M. Łożyńska, W. Barszcz, S. Sowa, and P. Wieciński, "Microfiltration membranes modified with zinc by plasma treatment," *Membranes*, vol. 13, no. 4, p. 387, 2023. [Online]. Available: https://doi.org/10.3390/membranes13040387. [Accessed: Jun. 15, 2024].
60. X. Li, Z. Zhao, Z. Qu, X. Li, Z. Zhang, X. Liang, J. Chen, and J. Li, "A Review of Traditional and Emerging Residual Chlorine Quenchers on Disinfection By-Products: Impact and Mechanisms," *Toxics*, vol. 11, no. 5, p. 410, 2023. [Online]. Available: https://doi.org/10.3390/toxics11050410. [Accessed: Mar. 7, 2024].
61. Q. Li, C. Reeve, L. Martinez, and S. Wright, "Scale-up in Biotechnology," in *Comprehensive Biotechnology*, 3rd ed., M. Moo-Young, Ed. Pergamon, 2019, pp. 919–932. [Online]. Available: https://doi.org/10.1016/B978-0-444-64046-8.00141-5. [Accessed: Feb. 26, 2024].
62. S. G. Salinas-Rodriguez, J. C. Schippers, and M. D. Kennedy, "The process of reverse osmosis," in *Efficient Desalination by Reverse Osmosis*, S. Burn and S. Gray,

Eds. IWA Publishing, 2016. [Online]. Available:https://www.researchgate.net/publication/302909917_The_process_of_reverse_osmosis. [Accessed: May 22, 2024].

63. A. A. Ahuchaogu, O. J. Chukwu, A. I. Obike, C. E. Igara, I. C. Nnorom, and J. B. O. Echeme, "Reverse osmosis technology, its applications and nano-enabled membrane," *International Journal of Advanced Research in Chemical Science*, vol. 5, no. 2, pp. 20-26, 2018. [Online]. Available: http://dx.doi.org/10.20431/2349-0403.0502005. [Accessed: Nov. 4, 2023].

64. K. G. Varshney, N. Tayal, and U. Gupta, *"Acrylonitrile based cerium (IV) phosphate as a new mercury selective fibrous ion-exchanger: synthesis, characterization and analytical applications," Colloids and Surfaces A: Physicochemical and Engineering Aspects,* vol. 145, no. 1-3, pp. 71-81, 1998. [Online]. Available: https://doi.org/10.1016/S0927-7757(98)00657-8. [Accessed: Jun. 21, 2024].

65. N. Ramzan, N. Feroze, M. Kazmi, M. A. Ashraf, and S. Hasan, "Performance analysis of cation and anion exchangers in water treatment plant: An industrial case study," *Polish Journal of Chemical Technology*, vol. 14, no. 2, pp. 35–41, 2012. [Online]. Available: https://doi.org/10.2478/v10026-012-0068-3. [Accessed: Apr. 23, 2024].

66. S. O. Skipton and B. I. Dvorak, "G08-1491 Drinking Water Treatment: Water Softening (Ion Exchange)," University of Nebraska. [Online]. Available: https://www.researchgate.net/publication/282225577_G081491_Drinking_Water_Treatment_Water_Softening_Ion_Exchange. [Accessed: May 30, 2024].

67. A. K. Shrestha and N. Basnet, "Variation of electrical conductivity of different sources of water with temperature and concentration of impurities - The UGC Small RDI Grant Report - 2016," [Online]. Available: http://dx.doi.org/10.13140/RG.2.2.34190.41284. [Accessed: May 29, 2024].

68. K. Jothivenkatachalam, A. Nithya, and S. Chandra Mohan, "Correlation analysis of drinking water quality in and around Perur block of Coimbatore district, Tamil Nadu, India," *Rasayan J. Chem.*, vol. 3, no. 4, pp. 649–654, 2010. [Online]. Available: https://rasayanjournal.co.in/vol-3/issue-4/8.pdf. [Accessed: Oct. 12, 2023].

THIS PAGE OF
TECHNOLOGICA ACTA
INTENTIONALLY LEFT BLANK