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A Laboratory Investigation To Remove The Responsible For Clogging In Filtration Process

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ABSTRACT

This work was executed to design and construct a scale plant as part of a water treatment process by combining filtration and disinfection in one unit, using the local medium of sand, and a Pulse Electric Field-Low Voltage (PEF-LV). The Existing Rapid Sand Filtration (ERSF) is a purely physical method of drinking water purification. Biofilm formation takes place in the sand medium and comprises three steps i) bacterial cells settle onto the sand medium, ii) cells proliferate and secrete adhesive Extracellular Polymeric Substrates (EPS) and iii) cells detach and spread the biofilm to new locations, forming a soapy substance. In this study, we attempted to modify the ERSF by overcoming the drawbacks, in terms of the quality of the filtered water, EPS removal, as well as ease of operation–maintenance to make it more sustainable. The Disinfectant of Rapid Sand Filter (DRSF) incorporates the Pulse Electric Field-Low Voltage through the electrodes between the media. The experiments were done over the period from December 2019 to July 2020, at 8 hr/day as the running time The effectiveness of the various operational conditions of the DRSF and their findings were also analyzed, together with the observational, experimental and theoretical basis. The results showed that the optimum conditions for better performance of the DRSF include 30V, 3 pulses/second, AC pulse frequency, 50Hz, two pairs of electrodes in the sand medium, 100 L/hr influent flow rate, and parallel connection. Backwashing requirements for the ERSF was necessary every day, but in DRSF it was only once in every 7 days, at the same influent flow rates of 100 L/hr. Therefore, as the DRSF is to be backwashed less frequently, the operation and maintenance difficulties will be greatly minimized. The EPS, which was produced by the bacteria, was responsible for clogging the medium and causing the necessity to backwash every day in the ERSF. This microbial biomass reduced the pore space in the medium and increased the head loss.

1. Introduction

Day by day, it is becoming more evident that the drinking water quality is steadily deteriorating. Hence, it has become an urgent need to supply clean and safe drinking water to the public (Mohsin et al., 2013; Bowen et al., 2003). Rapid Sand Filters (RSFs) evolved towards the end of the 19th century in the United States and quickly gained popularity. The

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RSF is a purely physical method of purifying drinking water. It provides rapid and efficient removal of the relatively large suspended particles. For the provision of safe drinking water, the RSFs necessitate adequate pre-treatment (coagulation–flocculation) and post-treatment (disinfection, using chlorine). Both the operation and construction are cost-intensive. This is a relatively sophisticated process, normally requiring power-operated pumps, regular backwashing or cleaning, and flow control of the filter outlet (Tatari et al., 2017, 2016; Erokhina et al., 2020). As the inlet water contains large groups of bacteria that are trapped in the sand medium, in the conditions suitable for them, it encourages the growth and increase of the bacteria. Biofilm formation involves three steps (i) Bacterial cells settle onto the sand medium, (ii) Cells proliferate and secrete adhesive extracellular polymeric substrates (EPS) and (iii) Cells detach and spread the biofilm to new locations, A soapy substance is formed which clogs the pores in the sand medium (Visick et al., 2016). Extracellular Polymeric Substances (EPSs) are the natural polymers, of high molecular weight, secreted by the bacteria into their environment (Seviour et al., 2019).

Although the existing granular filter medium such as sand is adequate to treat turbid water, finding an alternative filter medium or a new technique is also extremely necessary and is becoming popular because it will help to minimize the treatment costs, and improve the removal efficiency compared to the conventional medium and methods being used (Jusoh et al., 2006; Nakamura et al., 2020). Several investigations had been conducted to modify the filtration and disinfection units employed in the water treatment plants, using different methods. Al-Tufaily and Zwayen (2015) examined the feasibility of using the filings of solid wastes like glass, aluminum, and plastic, as a filter medium (Al-Tufaily and Zwayen, 2015). Kholoma (2017) tested the biochar material and sand medium in laboratory-packed bed reactors and field-constructed filter beds for the removal of the turbidity and other pollutants discharged from small-scale (Kholoma, 2017). Zheng et al. (2013) described a pulsed low-electric field process for water disinfection (Zheng et al., 2013). Varkey et al. (2017) explored the application of moderate electric or magnetic fields for the treatment of E. coli-contaminated deionized water (Varkey et al., 2017). Zhu et al. (2017) studied the potential of low-voltage PEF to inactivate vaccinated microorganisms in blueberry (Zhu et al., 2017). Ramaswamy et al. (2019) focused on the inactivation of naturally prevalent Escherichia coli and fecal coliform bacteria in environmental water using titanium electrodes (Ramaswamy et al., 2019). Among novel, emerging techniques PEF-LV is one of the most promising in order to achieve a gentle, disinfection, non-thermal pasteurization or cell disintegration. First applications of pulsed electric fields were put forward in the 1960s. First attempts in the 1980s, to realize industrial equipment were prepared, but it took until 2005 to achieve the first commercial use. From the literature surveyed, this is a new study in which the use of Pulse Electrical Field Low Voltage (PEF-LV) is investigated, used in the sand filter which connects two processes (filtration and disinfection) in one unit, called the Disinfectant Rapid Sand Filter, (DRSF) for potable water. DRSF-treated water intends to achieve the international standards set for potable water, in terms of physical and microbiological quality. The aims of this study are to modify the rapid sand filter, ensuring high yield, long filter run, and easy operation and maintenance, as well as avoidance or reduction in the use of chlorine in the disinfection unit.

2. Materials and methods

2.1. Materials

The materials used in this work are included in two set-ups (i) the experimental setup for ERSF and DRSF, and (ii) the experimental laboratory, as listed in Table 1.

2.2. Method

The experimental set up was done, adopting the basic design of the Existing Rapid Sand Filter (Abu-Khistawi Water Treatment Plant). In the set-up, two PVC pipes, 15 cm in diameter and 350 cm in height, were used as a packed column filter. The PVC material revealed the following properties: easy to install, lightweight, strong, durable and easily recyclable, as well as cost-efficient and sustainable. A 5 x 350 cm transparent glass was fixed onto the filter column, across the length, in order to observe the performances of filtration and backwashing. The entire filter media were washed with clear water. Both the filter media were placed individually in a vertical pipe, one represented the ERSF, while the other denoted the DRSF. The packed media for both columns were identical, and the total depth of the sand and gravel media was 120 cm. For the modified filter, the Pulse Electric Field-Low Voltage (PEF-LV) was selected, based on the configuration defined. Head loss ports (piezometer) were drilled on either side of each column. Provision was made to collect samples at different times, through valves connected to the effluent pipes. Besides, the arrangement was made in such a way to measure the head loss at different times and depths. Packed column filters were installed using a stand on the flat surface, using PVC fittings. Two tanks, 500 liters in capacity, were provided; one was used for raw water, and the other for backwashing. Each tank was connected to a pump. The influent flow rate was controlled by a flow meter and a valve between the feed tank and the packed column filter. An overflow outlet was provided to maintain a constant head. The tops of the columns were protected by a removable PVC cap having two holes for the inlet and ventilation. A perforated base was provided across the entire cross-section of the column to ensure even distribution of the raw water, as well as to achieve uniform flow conditions in the filter medium. Water flowed from the feed tank to the top of the column through a flexible PVC pipe (1.12 cm in diameter) and then trickled vertically in the downward direction, via gravity flow, through a series of

Table 1
The materials that utilized of carried out ERSF and DRSF.

Materials of scale plant and apparatus	Information
Filter column	Polyvinyl chloride (PVC) diameter of 0.15 m, length 2 m, a cross-section area 0.0176 m^2.
Filter media	Conventional filtration (local sand and support gravel)
Electrode	Three metals: aluminum, copper and silver.
Silver electrodes	The silver electrodes were prepared by the researchers, diameter (1 mm) and Electrical resistivity 15.87 nΩm at 20 °C.
Adaptor power	Voltage change regulator model 001.
Pulse frequency device	Model (kb-sk07) measure the number of pulse per second.
Power supply	Alternating Current AC and Direct Current DC
Inlet and outlet pipe	PVC diameters of 0.0125 and 0.0375 m,
Influent water	water from filtration process
Water tank	500 L stainless-steel
Flow meter	(0.25–4 Lpm)
Water pump	Flow rate 10–30 L/min, head 4–30 m, the maximum liquid temperature 40 ± 1 °C.
Laboratory materials and apparatus	**Information**
Scanning Electron Microscopy, (SEM), Philps CM10, Holland	Morphology of bacteria.
Urinary Tract Infections (UTIs) media	Account of bacteria (CFU/ml), The dehydrated medium was homogeneous, available, easy to apply, and gives accurate results for the main types of bacteria present in water samples, free flowing, and beige in color.
Culturing Hood, LBC-1203B-B2, Korea.	Creating a sterile environment for cell.
Incubator, LIB-030M, Korea.	Growing and maintaining cell cultures.
Autoclave, TR250N, Korea.	Steam sterilization pressure to kill bacteria, viruses, fungi, and spores
Turbidity meter, Lovibond turbidity check infrared 0–1100 NTU	Measuring turbidity.

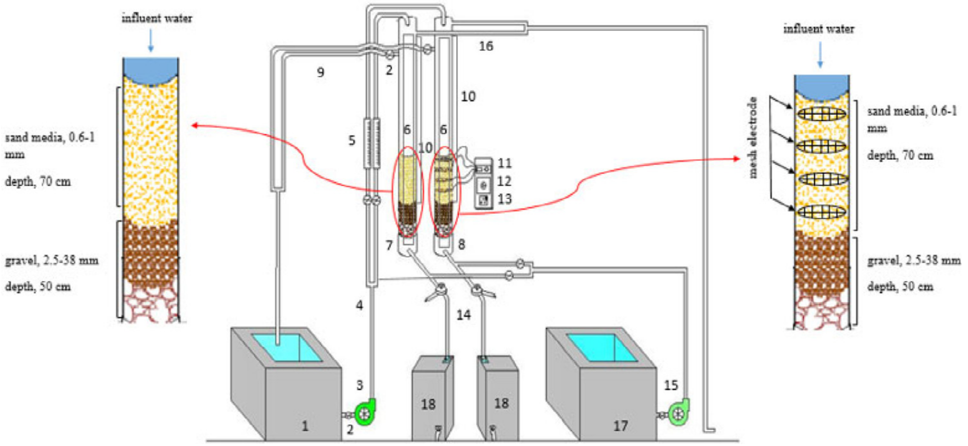

Fig. 1. Experimental setup, (1) feed tank, (2) valve, (3) raw water pump, (4) pipes of raw water, (5) flow meter, (6)glass, (7) ERSF, (8) DRSF, (9) over flow pipe, (10) piezometer, (11) voltage change device, (12) pulse frequency device, (13) point of power supply, (14) pipes of filtered and sample water. (15) backwashing pump, (16) effluent backwashing pipe, (17) backwashing tank and (18) collection containers.

differently graded filter materials. This reduced the turbidity, as well as ensured improvement in the bacteriological water, via the perforated, false 10-cm thick PVC base, provided at 25 cm above the bottom of the column. A fixed filter control and regulation flow meters were provided at the inlet of each filter compartment to ensure constant filtration rate. Two flexible piezometric pipes were provided in each column to record the development of head loss during the filter run. The diagram of the scale plant experimental setup is shown in Fig. 1. A drain system was provided at the top sidewall of the filter column to ensure that the supernatant water of the backwash drains out. Two pipes (2.5 cm in diameter), one for the ERSF column and the other for the DRSF column, were used as wash-out pipes.

Table 2
The physicochemical characteristics for raw and filtered water.

Physicochemical characteristics	Raw water				Filtered water			
	Av.	Min	Max	St. dev.	Av.	Min	Max	St. dev.
Turbidity, (NTU)	22.75	10.2	35.3	12.55	3.1	0.9	5.9	2.5
pH	8	7.7	8.3	0.3	7.6	7.2	8	0.4
Temperature, (°C)	22.95	13.8	32.1	9.15	23	13.6	32.4	9.4
Total dissolved solid, (mg/L)	1065	621	1510	444.5	1068	604	1533	464.5
Electrical conductivity, (μmohs/cm)	1234	818	1650	416	1245	820	1671	425.5
Total hardness as ($CaCO_3$), (mg/l)	408	320	496	88	405	325	486	80.5
Alkalinity as ($CaCO_3$), (mg/l)	126	106	146	20	130	115	145	15
Chloride, (mg/l)	95	65	125	30	96.5	68	125	28.5
Calcium, (mg/l)	92.5	64	121	28.5	94	70	118	24
Magnesium, (mg/l)	45.5	30	61	15.5	45	30	60	15

3. Results and dissection

The results are presented and discussed with reference to the aims of this study, which include a description of the performance assessment of the ERSF and DRSF. Besides, it presents the results of the effect of the crucial parameters, (physicochemical and bacteriological characteristics of the raw and filtered water), on the efficiency of the ERSF and DRSF. The effectiveness of the various operational conditions of the DRSF and their findings were also analyzed, as well as the observational, experimental and theoretical basis. Focused and vigilant observations were made to assess the removal of the turbidity and bacteria, with respect to the various operational parameters of the PEF-LV filter media.

3.1. Existing rapid sand filter (ERSF)

The scale plant of the ERSF was designed and constructed to simulate the sand filter in a conventional water treatment plant. The influent water entering this plant was the raw water collected from the Al Hillah River, in Babylon, Iraq.

3.1.1. Physicochemical characteristics

The average, minimum, maximum and standard deviations of the physicochemical characteristics of raw and filtered water are listed in Table 2.

3.1.2. Bacteriological analysis

Bacterial pathogens are removed through mechanical trapping and adsorption. Mechanical trapping occurs via two methods: the first is through surface filtration, whereby particles that are too large to pass through the pore are prevented from entry. The second is through the depth filtration, where the particles that penetrate the filter are trapped. The raw water samples were taken in a test tube, and filtered via a valve that is regularly used and easily accessible. After culturing the samples, four main types of bacteria (E. coli, S. aureus, E. aerogenes and K. pneumoniae) were identified. Fig. 2A shows the account of the bacteria found in the raw and filtered water samples. The method used to investigate the bacterial growth to obtain the samples of interstitial water and particulate medium at 10 cm depth from the surface was the constructed sampler/corer one. Almost at the onset of the ERSFF operation, no bacterial colonies were present in the sand medium (Fig. 2B). The first distinct development of the bacterial colonies forming a biofilm was observed and they gradually began increasing after four days. The biofilm patches were formed on the surfaces and in the cracks of the medium.

The biomass in the filters was characterized by quantifying the bacterial abundance and activity, as well as the concentration of the extracellular polymeric substances (EPS). The results of this study revealed that the clogging effects were, to a large extent, attributed to the presence of the EPS (Fig. 2C). This microbial biomass reduced the pore space in the medium. The most severe clogging was noted to occur in the top 5–10 cm of the filters, where bacterial abundance and activity were at the highest, and the deeper layers of the filters were gradually clogged. This work attributes the clogging effects observed to the bacteria-generated EPS, whereas the bacterial cells by themselves were found to exert a negligible influence on the pore space occupied. On comparing the different causes for the sand filters getting clogged with particle deposition, it appears that the EPS produced and head loss might have been responsible for the clogging.

3.2. Disinfectant rapid sand filter (DRSF)

Pulse Electric Field-Low Voltage is responsible for the destruction or inactivation of the bacteria and this is achieved by the breakdown of the bacterial cells during exposure to an electric field. First, holes are made, after which the external walls of the microbial cells rupture, leading to the inner contents leak in gout, resulting in the death of the pathogenic bacteria. The pathogenic cells get destroyed, thus causing a reduction in the growth and reproduction of the microbes which contribute to the infections. In Fig. 3, the DRSF mechanism is explained, through the treatment (inactivation) of the bacteria, which occurs inside the column filter, and the behavior of the silver mesh, (electrode) through the application of the PEF-LV. Many factors, which contributed to the performance of the DRSF as agents of inactivation of the bacterial growth through the filtration process, were organized.

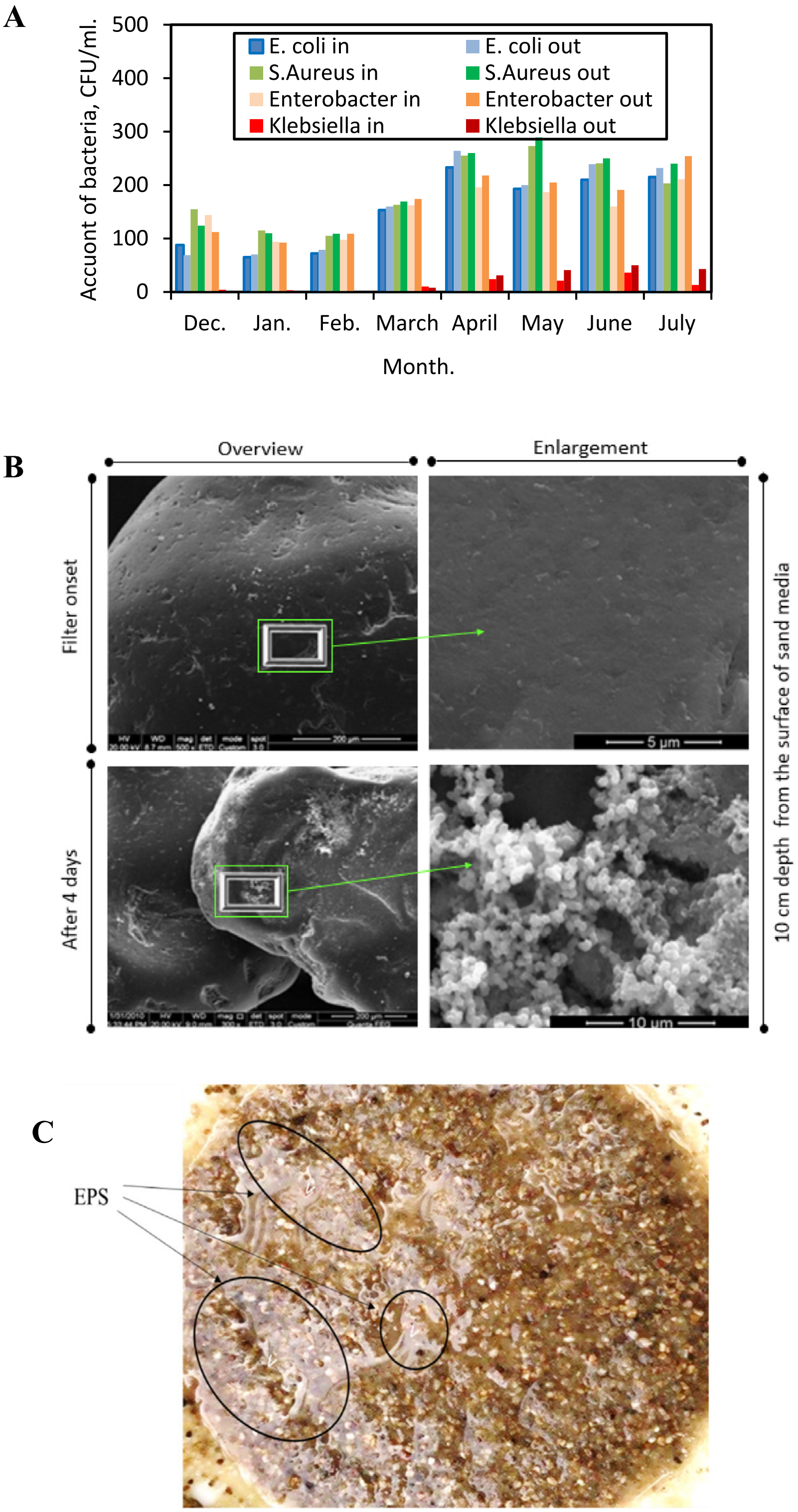

Fig. 2. (A) Account of bacteria before and after ERSF process, (B) Representative SEM images showing the spatial (media) and temporal (filter onset and after 4 days) fluctuations of the microbial coverage on the filtration media, C: Depicts EPS in the sand media.

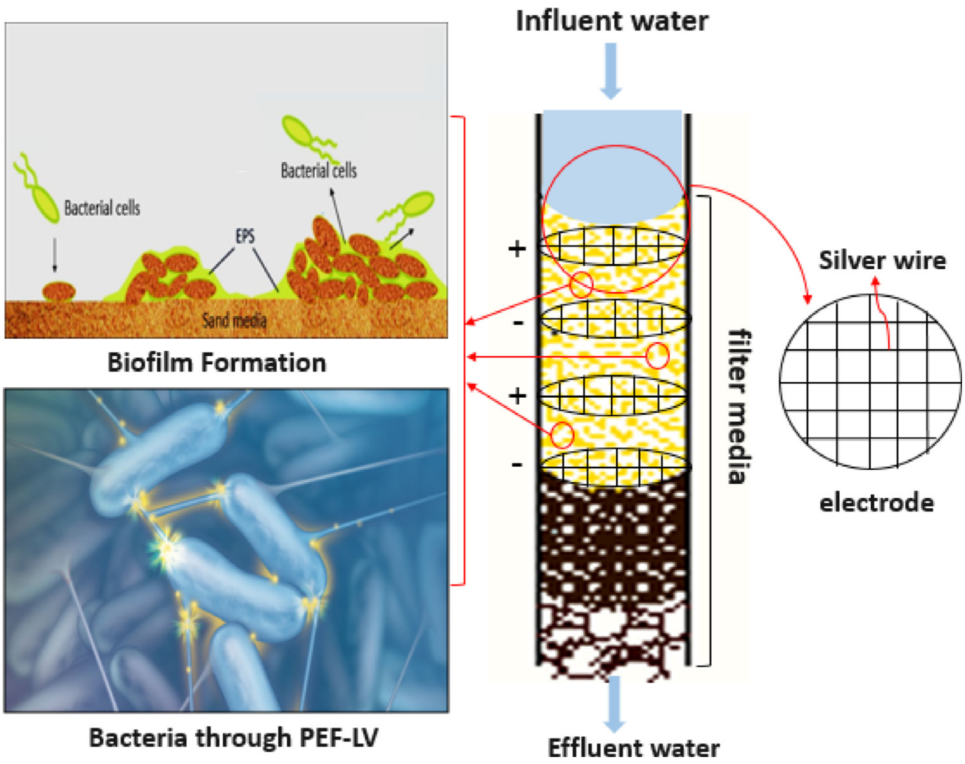

Fig. 3. Mechanisms of DRSF.

3.2.1. *Effect of electrode materials*

The most important factor is the selection of materials, which affects the electrodes in terms of performance and durability. The design of the electrode includes a circular mesh that is compatible with the diameter of the column filter and allows the water to pass through it. Three different materials namely, aluminum, copper and silver, were tested as electrodes. The experimental results were taken randomly for six raw water samples (Fig. 4A) after comparisons were made among the three candidate materials, under the same conditions (one pair of electrodes, 30 V, 25 °C and 1 min). The aluminum achieved over 55%–60% of bacterial removal, while the copper and silver performed better than the aluminum, where bacterial removal of around 77%–98% was achieved. This demonstrated that both copper and silver were suitable as materials for DRSF electrodes.

To demonstrate the relative corrosion resistance of copper and silver, one piece each of the copper and silver meshes were placed in a bottle containing 250 mL of raw water, for 30 days. The tolerance of each material to corrosion is shown in Fig. 4B, where green precipitates were observed only on the copper mesh, and no observable change was evident on the silver mesh. The green precipitate was formed due to the reaction of the copper metal with the water salts. Silver is the best conductor of electricity because it contains a greater number of free electrons, which induces an increase in the conduction of electricity. Therefore, silver was the material selected as the mesh electrode.

3.2.2. *Effect of Alternating Current (AC) pulse frequency*

The effects of pulse frequency (1, 2, 3 and 4 pulse/second) on the DRSF performance, at different voltages applied (0–30) V, 50 Hz, with two pairs of electrode meshes in the sand medium (s.m) were tested. Fig. 4C demonstrates that at 1 pulse/second, low removal efficiency of the bacteria was achieved, while the best pulse frequency was observed at 3 pulses/second when higher removal efficiency was attained. However, when the pulse frequency increased to 4 pulses/second, there was no increase in the removal efficiency. Therefore, in this study, the 3 pulses/second was selected as the optimal frequency, as well as to avoid the adverse effects like electrolysis-induce electrode corrosion (Hung, 2015).

3.2.3. *Effect of applied voltage*

The voltage applied has a crucial part to play in the DRSF performance, as it is the main contributing factor to the strength of the electric field applied (Hung, 2015). From the economic perspective and safety concerns, the voltage used ranged from 0 to 30 V, 50 Hz and 3 pulses/second. The experimental results are shown in Fig. 4D, where it is evident that as the applied voltage increased, the removal efficiency of the bacteria improved. These results are consistent with the findings of other researchers, namely, (Hung, 2015; Bonaventura et al., 2020; Rond et al., 2020). An increase in the

Table 3
Calculation of EFS.

Applied voltage (V)	First case: sand media (s.m)				Second case: filter (sand and gravel) media (f.m)			
	*EFS at n = 1, d = 35	RE, %	EFS at n = 2, d = 17.5	RE, %	EFS at n = 1, d = 60	RE, %	EFS at n = 2, d = 30	RE, %
15	0.42	21.8	0.88	45.3	0.25	9.8	0.50	31.9
20	0.57	32.5	1.18	62.8	0.33	19.7	0.67	45.6
25	0.71	57.6	1.47	78.2	0.42	33.4	0.83	61.3
30	0.86	65.4	1.76	94.11	0.5	50.2	1.0	70.1

* EFS (V/cm), n = number of electrode pair, d = distance between electrode (cm), and RE, % = average removal efficiency of bacteria.

voltage applied resulted in an increase in the Electric Field Strength (EFS); the higher the EFS, the easier it is for the transmembrane potential to exceed the critical value of electroporation. Once the critical value was crossed, structural rearrangement of the phospholipid bilayer membrane occurred, causing pores to form on the bacterial cell membrane. This facilitated the easy entry of the foreign material, such as chlorine, into the bacterial cell, thus producing a better bactericidal effect. Therefore, this study selected 30 V as the best voltage for all the experiments done while studying the DRSF performance. Very low removal efficiency was noted when the voltage applied dipped below 15 V. Therefore, the results of the removal efficiency with (0–15) V are not shown in this Figure. Besides, it tested the performance of the DRSF in terms of bacterial removal, and hence, the Scanning Electron Microscope (SEM) was utilized to determine the morphological structures of E. coli, and S. aureus, before and after applying the PEF-LV. The deformity in the E. coli morphology indicated the capability of the PEF-LV to completely destroy the bacteria. The different stages involved in the bacterial destruction are shown in Fig. 4E. The changes in the cell wall morphology in the influent water (normal cell shape with undamaged structure of the inner and intact outer membranes) and that in the effluent water was the peptide-induced breakage and roughness in the cell wall. Increasing damage to the cell wall of the microorganism was evident in the form of cracks developed as the voltage was increasing to 30 V. Cell shrinkage was also noted due to the loss of turgor.

3.2.4. Effect of electrodes number

After investigation from the earlier sections, the optimum voltages were found to be 30 V, 50 Hz and 3 pulses/second; this paragraph investigated the number of mesh electrodes required for obtaining the best design for DRSF. According to (Hung, 2015; Rond et al., 2020) the removal efficiency can increase by increasing the number of electrodes. Therefore, the different numbers and distribution of the electrode pairs (gap distance) of the packed column filter were investigated. Two cases of electrode distribution in the column test were installed and then examined. The first case explained the position of the electrode meshes in the *sand medium (s.m)*, while the second case investigated the electrodes in the *filter medium* (f.m), which indicates the sand and gravel media. The distance between the electrodes was the distance between the positive and negative electrodes. The EFS are affected by two factors: (i) applied voltage and (ii) distance between two electrodes. An increase in the voltage applied will result in increased EFS, and a decrease in the distance between two electrodes will also result in increased EFS. Hence, EFS can be defined using the following Eq. (1).

$$\mathrm{EFS} = \frac{\mathrm{V}}{\mathrm{d}} \tag{1}$$

where:
EFS: the electric field strength.
V: the applied voltage.
D: the distance between two electrodes.

According to Eq. (1), the calculated voltage applied with different distances of the column test ranged from 15 to 30 V. Two cases were studied. *Case 1* one and two pair were set inside the sand media at distances (35 and 17.5 cm) respectively. *Case 2*: one and two pair were set along filter media (sand and gravel) at distances (60 and 30 cm) respectively. In Table 3, it is clear that at higher EFS, better performance in bacterial inactivation (removal efficiency of bacteria) is achieved. Several researchers reported that higher EFS would be best for bacterial inactivation (Hung, 2015; Rond et al., 2020; Wang et al., 2018; Upadhyay et al., 2019).

Eq. (2) was another method of explanation to confirm that an increase in the number of electrode pairs triggered an increase in the removal efficiency of the bacteria. The effective inactivation area is, therefore, proportional to the number of mesh electrode pairs. When the number of mesh electrode pairs increases, the effective inactivation area also increases, according to the following equation (Barbosa-Canovas and Zhang, 2019).

$$\text{Effective inactivation area } (\mathrm{cm}^2) = [(2 \times \mathrm{n} - 1) \times \mathrm{A}] \tag{2}$$

where:
n: the number of mesh electrode pairs.
A: the area of the mesh electrode, cm^2.

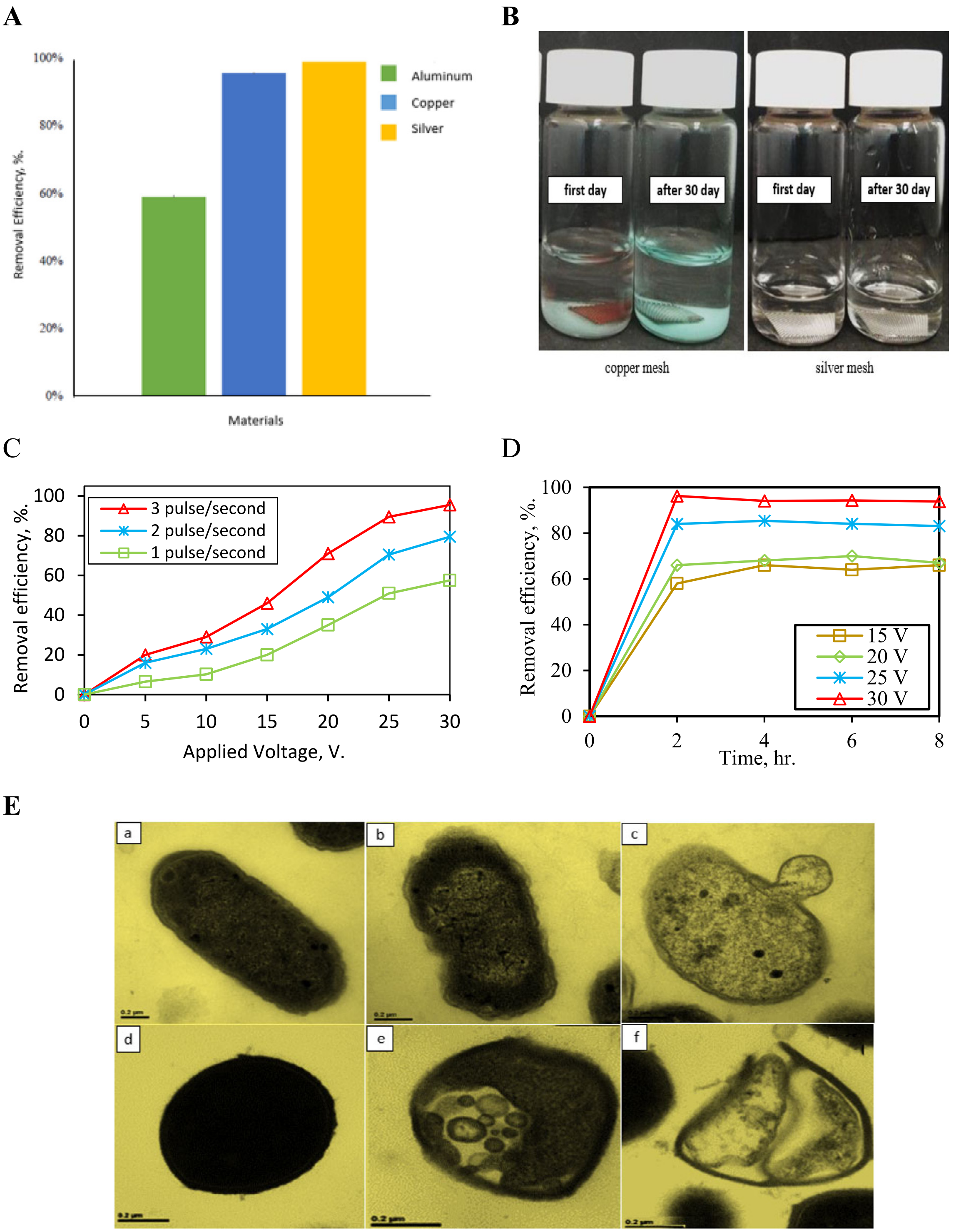

Fig. 4. (A) Effect of electrode material type towards bacteria removal efficiency, (B) Corrosion test, (C) The effect of AC pulse frequency on the removal efficiency of E. coli at 50 Hz, 2-pair mesh electrode in s.m, 100 L/hr, and parallel connection, (D) Effect of applied voltage on removal efficiency of bacteria at 30 V, 50 Hz, 3 pulse/ second, 2-pair mesh electrode in s.m, d = 17.5 cm, 100 L/hr, and parallel connection, (E) SEM image of E. coli (a) before PEF-LV, (b and c) after PEF-LV (deformed and bursting of E. coli cell), and S. Aureus (d) before PEF-LV, (e and f) after PEF-LV (deformed and bursting of S. Aureus cells). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The effective electrode areas were 308 cm^2 and 616 cm^2, when single and double pairs of electrodes were used, respectively. The retention time of the bacteria between the electrodes increased when the number of the electrode pairs was increased. Hence, as the exposure time of the cells to the electrical field became longer, the performance too was better (Stulić et al., 2019; Estifaee et al., 2019).

3.2.5. Effect of electrodes connection method

Components of an electrical circuit can be connected either in series or in parallel. The connection of the electrodes in series is done along a single conductive path, to ensure that the same current flows through all of the electrodes, but the voltage gets dropped (lost) across each of the electrodes. The sum of the voltages consumed by each individual electrode is equal to the source voltage (Anwer and Majeed, 2020). While the parallel electrode connections are connected along multiple paths to ensure that the current can split up, the same (constant) voltage is applied to each mesh electrode and is equal to the source voltage (Ozyonar, 2016; Wang et al., 2019). Therefore, the parallel connection method was adopted in this study, by applying Eqs. (1) and (2), and using the parallel connection (same voltage in each electrode), Fig. 5(A to D) are drawn. The maximum removal efficiency for all the types of bacteria was achieved under the following conditions viz., 30 V, 3 Hz, 2pairs of the mesh electrodes in s.m, with 17.5 cm distance between the electrodes and parallel connection. While the minimum % of the REs was recorded at (30 V, 50 Hz, 3 pulses/second, one pair of electrodes in f.m, was present with 60 cm distance between the electrodes and parallel connection. The account of E. coli was the largest account of bacteria found in all the samples of the culture media. The average removal efficiency of E. coli was 92.4% (Fig. 5A). The highest removal efficiency of the E. coli was 96.4%, in February, while the lowest removal efficiency of E. coli was 88.4%, in April. The average temperature in this month was conducive (30 °C) and may be responsible for increasing the bacterial growth (increasing account). From the culture medium, S. aureus was the second account of bacteria after E. coli, with an average removal efficiency of 93.5% (Fig. 5 B), while the maximum and minimum removal efficiencies of S. aureus were 96.8% and 90.2% in February and April, respectively. In Fig. 5C the average removal efficiency of E. aerogenes (93.1%) was presented, while the best removal efficiency of the E. aerogenes was 97% in February, with the least removal efficiency of the E. aerogenes was 89.1%, in April. The lowest account of bacteria found in the culture media plates was Klebsiella, which had an average removal efficiency of 97.5% (Fig. 5D).

3.2.6. Effect of electric field direction (EFD)

When the battery is the electric source (direct current DC), the direction of the EF plays an important part in the DRSF performance. In DC, the electrons flow steadily in a single direction, (i.e. forward). The effect of the EFD was studied by connecting the electrode to have EF parallel, but opposite, to the direction of water flow.

In the EFD parallel to the water flow, the resultant force (F_{net} parallel) exerted on the bacterial cell was obtained from two forces: one exerted upon the bacterial cell wall by the water flow (F_w) and the other exerted upon the bacterial cell wall by an electric field (F_{EF}). While the resultant force (F_{net} opposite) exerted on the bacterial cell also resulted from two forces, namely, the force exerted onto the bacterial cell wall by the water flow (F_w) and the one exerted upon the bacterial cell wall by the electric field ($-F_{EF}$) in the direction opposite to that of the electric field, induced by the water flow. Therefore, F net parallel > F net opposite, and by Newton's third law of motion, the following equation was obtained.

$$F_{net} = \frac{m \times v - m \times u}{t} \tag{3}$$

where:
m is the mass of the bacteria cell, kg.v is the velocity of water, m/s
u is the initial velocity of water, m/s
t is the time needed by the bacterial cell to travel through the electrodes, s.
Since the mass of the bacteria cell and the velocity of water remained unchanged, Eq. (3) can be simplified to the following.

$$F_{net} = \frac{m \times v}{t} \tag{4}$$

According to Eq. (4), the force a bacterial cell exerted was inversely proportional to the time in which the bacterial cell traveled in the electrodes. The resultant force that the bacteria experienced was less when the EFD was in the direction opposite to the water flow, and the time the bacterial cell needed to travel in the electrode was longer; the time for which the bacterial cell was exposed to EF was longer; and, hence, the bactericidal performance was relatively higher. From Fig. 5E it is evident that the removal efficiency of the E. coli when the EFD applied was parallel and opposite to the water flow was 80 and 95.4%, respectively.

3.2.7. Effect of PEF-LV on physicochemical characteristics

The variations in the physicochemical characteristics, related to the filtration process, such as turbidity, pH, temperature, total dissolved solid, electrical conductivity, total hardness, alkalinity, chloride, calcium, and magnesium, have been analyzed for both the raw and filtered water, in this study. The turbidity is due to the wide variety of suspended matter, ranging in size from colloidal to coarse dispersion, depending upon the degree of turbulence. It ranges from pure inorganic substances to those that are highly organic in nature (Tripathy and De, 2006). It is utilized as an indicator to ensure adequate quality of the intake water into the treatment plant. The turbidity of the raw water varied from test to test, mainly due to seasonal changes. Three different raw water turbidities were identified (10–15, 15–25 and 25–35) NTU, and during each run the optimal conditions were maintained at constant.

On average, the removal efficiency of turbidity was 94.5% under the conditions where n = 2 and the electrodes were embedded in the sand medium, as shown in Fig. 5F. In the absence of an electric field (zero voltage), the particles were entrained and captured in this medium due to the short-range van der Waals forces. In the water phase, most of the natural particles, including the biological colloids, carry some negative surface charge. Similar to the effect of the gravity field, the application of PEF-LV with low voltage in the filtration process increased the probability of particle deposition on the electrode surfaces and between the sand medium by the additional migration velocity of these charged particles. The effect study of PEF-LV on the other physicochemical characteristics showed that there were no noticeable changes were observed in these parameters.

3.2.8. Head loss (HL)

Three factors can be used to determine when a filter needs backwashing, the length of the filter run, turbidity of the effluent water and head loss. Head loss is the loss of pressure (head) caused by water flowing through the filter. As the filter operates, it removes the suspended matter from the influent water. Eventually, this matter clogs the filter and the flow gets reduced. The difference between the level of water above the sand bed and the pressure at the outlet is known as head loss. Assessment of the head loss built up in the filter medium is a good indication of the efficiency of the performance of the prefiltration process of removal of the solids. Piezometers were installed under and above the sand medium. The water level in the piezometer was recorded at the start of each run and at fixed time intervals (every 2 hr) to determine the head loss. At zero voltage (ERSF), Fig. 6 (A to C) illustrate the relationship between the head loss with the times, at different flow rates (50,100 and 200 L/hr) and influent turbidities (15, 25 and 35 NTU) in order to simulate the filtration rate in conventional water treatment plant (rapid sand filter). At a low flow rate and low influent turbidity, the quantity of the suspended solids captured within the media is lower than at the high flow rate and high turbidity. Therefore, in this case, the head loss development is very slow. Maximum head loss was recorded at a flow rate of 200 L/hr and turbidity 35 NTU. The head loss develops due more to the particulate deposition than microbiological growth, at the start of filter run, to reach the 2-m height of the column, from the time of starting the operation. Based on the head loss (1.6–2) m and effluent turbidity > 5NTU the column filter needs to be backwashed by clean water. When the voltage is applied, the head loss developed during the operation runs is plotted at different turbidities and flow rates, as depicted in Fig. 6 (D to F). Many observations from these Figures have been drawn, as stated below:

- The head loss increases slowly and continues to increase until it reaches a point at which the removal efficiency of the turbidity gradually begins to reduce.
- There is a positive relationship between the influent turbidity and flow rate with head loss.
- At the different flow rates (50, 100 and 200) L/hr, the backwashing without using air is done after 12, 7 and 3 days, respectively.
- The application of PEF-LV revealed the formation of EPS, which was responsible for clogging the porous media and increasing the head loss.

3.2.9. Dissolved oxygen (DO)

Dissolved oxygen (DO) is one of the clearest indicators of water quality. DO is best measured directly in the water using a dissolved oxygen meter (or DO meter). Water at lower temperatures will usually have higher mg/L of dissolved oxygen, while the warmer, polluted waters will have lower mg/L. Healthy water should generally have dissolved oxygen concentrations above 6.5–8 mg/L (Kannel et al., 2007). The results shown in Fig. 6G indicate that the DO concentration of filtered water is lower than that of the raw water. The lowest DO concentration was recorded during the summer season, due to the increase in temperature and bacterial growth, (Abdul Hameed M. Jawad et al., 2010; Al-Shujairi, 2013) as confirmed in this state. However, at DRSF, there were slight variations in the DO concentrations in both the raw and filtered water, during the period of study, where more than 90% of the bacteria were inactivated, which use the DO for growth. This finding concurred with the report of Abbas and Hassan, 2018.

4. Conclusions

This paper includes the concluding remarks, drawn from the performance study of the ERSF and DRSF. The major problems encountered in the conventional rapid sand filters were observed to be, poor performance in the removal of the fecal coliform bacteria (need for disinfection), shorter filter run (need for backwashing) and poor operation and maintenance. Developing ERSF is needed, as part of the water treatment process, by combining Filtration and Disinfection in one Unit to ensure water quality improvement, a long filter run (to reduce the frequency of backwashing) and reduction or elimination of chlorine. PEF-LV is an alternate water disinfection technology designed to avoid the use of chlorine, which is the cause for several health issues and carcinogenic diseases. Bacteria subjected to pulsed electric fields experience a change in the cell permeability and, on occasion, produces an irreversible hole that leads to cell death. Results show

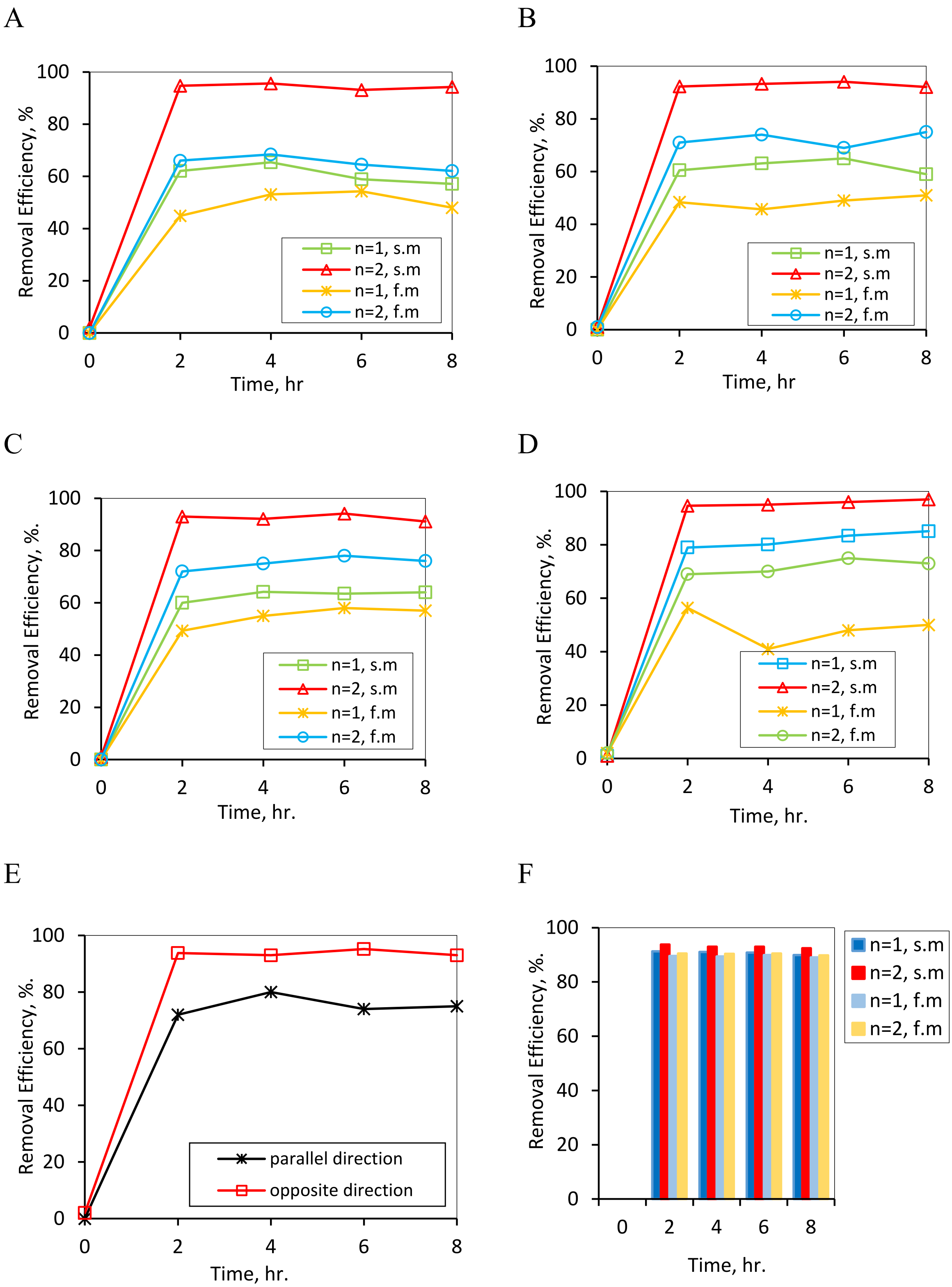

Fig. 5. (A, B, C and D) Effect of electrode number on average removal of E. coli, S. Aureus, E. Aerogenes and Klebsialla respectively in 30 V, 50 Hz, 3 pulse/ second, 2-pair electrode in s.m, d = 17.5 cm, 100 L/hr, and parallel connection, (E) Effect of DC parallel and opposite EFD with water on removal efficiency of E. coli., F) Effect of PEF-LV to average removal efficiency of turbidity in 30 V, 50 Hz, 3 pulse/ second, 2-pair electrode in s.m, d = 17.5 cm, 100 L/hr, parallel connection and opposite EFD to water flow.

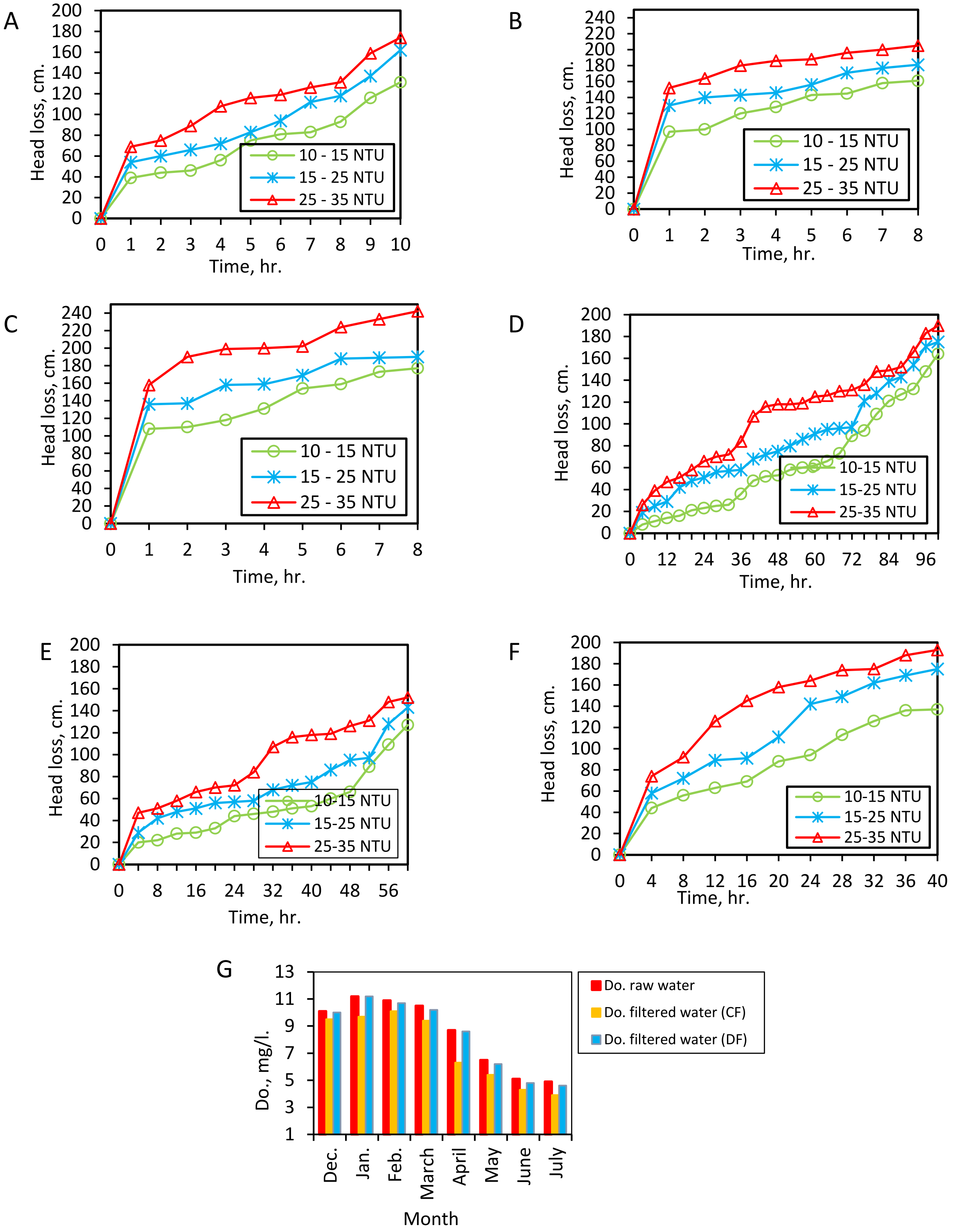

Fig. 6. (A, B and C) Head loss development in ERSF at flow rates, 50 L/hr, 100 L/hr and 200 L/hr. (D, E and F) Head loss development in DRSF at flow rates, 50 L/hr, 100 L/hr and 200 L/hr. (G) Variation of DO concentration of ERSF and DRSF.

that the optimum conditions for the higher performance of the DRSF are 30 V, 3 pulses/second, AC pulse frequency, 50 Hz, two pairs of mesh electrodes in the sand medium, 100 L/hr influent flow rate, and parallel connection. On bacteriological analysis, no removal efficiency of bacteria was found in the ERSF, while in the DRSF 94.12% was achieved. The average removal efficiency of turbidity in the ERSF was 88%, while it was 93.25% in the DRSF. Frequent backwashing requirements (due to the shorter filter run) of the ERSF precipitated difficulties in both operation and maintenance (every day backwashing), while in the DRSF, backwashing was necessary only on every 7th day, for the same influent flow rate of 100 l/hr. Therefore, the DRSF needed to be backwashed less frequently, greatly minimizing the operation and maintenance difficulties.

CRediT authorship contribution statement

Ghassan Abukhanafer: Conceptualization, Methodology, Writing - original draft preparation. **Alaa H. Al-Fatlawi:** Supervision, Reviewing and editing, Data curation. **Hasan Hamodi Joni:** Visualization, Investigation. **Huda M. Salman:** Linguistically and scientifically corrected.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdul Hameed M. Jawad, A., Haider, S.A., Bahram, K.M., 2010. Application of water quality index for assessment of Dokan lake ecosystem, Kurdistan region. Iraqi J. Water Resour. Protect. 2010.

Al-Shujairi, S.O.H., 2013. Develop and apply water quality index to evaluate water quality of Tigris and Euphrates Rivers in Iraq. Int. J. Mod. Eng. Res. 3 (4), 2119–2126.

Al-Tufaily, M.A.M., Zwayen, D.M.A.-M., 2015. Water filtration by using of glass, plastic and aluminum filings as a filter media. J. Impact Factor 6 (1), 80–98.

Anwer, E.A., Majeed, B.A.A., 2020. Different electrodes connections in electrocoagulation of synthetic blow down water of cooling tower. Iraqi J. Chem. Petrol. Eng. 21 (1), 1–7.

Barbosa-Canovas, G.V., Zhang, Q.H., 2019. Pulsed electric field processing: An overview. In: Pulsed Electric Fields in Food Processing. CRC Press, pp. 17–46.

Bonaventura, Z., et al., 2020. Fast pulsed electrical breakdown of water: electron multiplication in liquid ruptures. Bull. Am. Phys. Soc.

Bowen, W.R., Doneva, T.A., Stoton, J.A.G., 2003. Protein deposition during cross-flow membrane filtration: AFM studies and flux loss. Colloids Surfaces B 27 (2–3), 103–113.

Erokhina, S., et al., 2020. Modification of the porous glass filter with LbL technique for variable filtration applications. Colloids Surf. A 606, 125459.

Estifaee, P., et al., 2019. Mechanism of E. coli inactivation by direct-in-liquid electrical discharge plasma in low conductivity solutions. Sci. Rep. 9 (1), 2326.

Hung, K.P.S., 2015. Pulsed electric field electrode designs for water disinfection.

Jusoh, A., et al., 2006. Comperative performances of single and dual media filters of sand and burnt oil palm shell. J. Teknol. 45 (1), 43–52.

Kannel, P.R., et al., 2007. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environ. Monit. Assess. 132 (1–3), 93–110.

Kholoma, E., 2017. Fortification of Soil-Based Wastewater Treatment Systems with Versatile Ubiquitous Reactive Media for Enhanced Removal of Phosphorus and other Pollutants. Doktorsavhandling, KTH, TRITA-LWR PHD 2017: 04.

Mohsin, M., et al., 2013. Assessment of drinking water quality and its impact on residents health in Bahawalpur city. Int. J. Human. Soc. Sci. 3 (15), 114–128.

Nakamura, A., et al., 2020. Effects of calcium chloride and poly (N, N-dimethylaminoethyl methacrylate) on the filtration rate of a bentonite suspension and the examination of the filtration mechanism. Colloids Surf. A 603, 125265.

Ozyonar, F., 2016. Treatment of train industry oily wastewater by electrocoagulation with hybrid electrode pairs and different electrode connection modes. Int. J. Electrochem. Sci. 11 (2), 1456–1471.

Ramaswamy, R., Ramachandran, R.P., Gowrisree, V., 2019. High voltage pulsed electric field application using titanium electrodes for bacterial inactivation in unpurified water. Japan J. Food Eng. 20 (2), 63–70.

Rond, C., et al., 2020. Statistical analysis of a micro-pulsed electrical discharge in water. J. Phys. D: Appl. Phys.

Seviour, T., et al., 2019. Extracellular polymeric substances of biofilms: Suffering from an identity crisis. Water Res. 151, 1–7.

Stulić, V., et al., 2019. Quantitative microbial assessment for *Escherichia coli* after treatment by high voltage gas phase plasma. Innov. Food Sci. Emerg. Technol. 53, 26–35.

Tatari, K., Smets, B.F., Albrechtsen, H.-J., 2016. Depth investigation of rapid sand filters for drinking water production reveals strong stratification in nitrification biokinetic behavior. Water Res. 101, 402–410.

Tatari, K., et al., 2017. Density and distribution of nitrifying guilds in rapid sand filters for drinking water production: Dominance of Nitrospira spp. Water Res. 127, 239–248.

Tripathy, T., De, B.R., 2006. Flocculation: a new way to treat the waste water.

Upadhyay, N., et al., 2019. Pulse electric field processing of milk and milk products. In: Non-Thermal Processing of Foods. CRC Press (Taylor and Francis), Boca Raton, Florida, USA.

Varkey, A.J., Dlamini, M.D., Mkhonta, S.K., 2017. Decontamination of bacteria from water with moderate electric and magnetic fields.

Visick, K.L., et al., 2016. Biofilms 2015: Multidisciplinary approaches shed light into microbial life on surfaces. J. Bacteriol. 198 (19), 2553–2563.

Wang, M.-S., et al., 2018. A review of sublethal effects of pulsed electric field on cells in food processing. J. Food Eng. 223, 32–41.

Wang, J., et al., 2019. Effects of electrodes and electrical connections of piezoelectric layers on dynamic characteristics of radially polarized multilayer piezoelectric cylindrical transducers. J. Intell. Mater. Syst. Struct. 30 (1), 63–81.

Zheng, C., et al., 2013. Fresh water disinfection by pulsed low electric field. J. Phys. Conf. Ser.

Zhu, N., et al., 2017. Design of a treatment chamber for low-voltage pulsed electric field sterilization. Innov. Food Sci. Emerg. Technol. 42, 180–189.