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An experimental procedure to investigate the effects of supplementing a low-density magnetic field on the performance of removal efficiency within the Orbal reactor

Hooman Ghahremanzadeh[a], Amir Hossein Javid[a,*], Sara Allahyaribeik[b], Amir Hesam Hassani[a]

[a]*Department of Environmental Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran, Tel.: +98 21 448 65179; emails: a.javid@srbiau.ac.ir (A.H. Javid), ghahremanzadeh@ut.ac.ir (H. Ghahremanzadeh), ahhassani@srbiau.ac.ir (A.H. Hassani)*
[b]*Department of Industry and Energy, Science and Research Branch, Islamic Azad University, Tehran, Iran, email: s.allahyari@srbiau.ac.ir*

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ABSTRACT

The use of Orbal reactors for wastewater treatment by activated sludge is deemed efficient by various literature sources. Furthermore, it is interesting to determine the potential methodologies to improve removal efficiencies. This study aims to investigate the performance of removal efficiency when a magnetic field is incorporated within the reactor. In this experiment, two magnetic fields of different intensities (1.3 and 2 mT) were used. To generate these magnetic fields, several neodymium magnets were applied to the reactor. The experiment and sampling lasted approximately over a 156-d period to observe the performance of the reactor, with and without the application of a magnetic field. Upon the reactor achieving a steady-state, results were taken. It should be highlighted that, before application, four different inflows were discharged into the reactor to attain the optimum retention time. To confirm the validity, results from relatable studies were compared with this study's findings. Upon application of the magnetic fields, removal efficiencies of total nitrogen, chemical oxygen demand, and biochemical oxygen demand for five days increased by 11%, 6%, and 7%, respectively. Nitrate concentration in effluent had decreased by 21%. Furthermore, the food to microorganism ratio had decreased within a 13%–15% range. Results indicated, also, that the application of different strength magnetic fields had minor effects on removal efficiency.

Keywords: Magnetic activated sludge; Orbal oxidation reactor; Total nitrogen removal; Biochemical oxygen demand for five days; Chemical oxygen demand

1. Introduction

The extensive growth in the world population has resulted in a rapid increase in water usage and thus leading to an increase in water pollution problems [1]. As a result, the continuing development of wastewater treatment technology has received significant attention from both industrial and academic researchers. The oxidation ditch process, today, is extensively used in municipal and industrial wastewater treatment [2]. The inner, middle, and outer channels make up the concentric channels within the Orbal reactor. The Orbal oxidation ditch, as an enhanced activated sludge process provides several advantages over conventional methods [3], which includes: higher reliability within the process, simpler operation, less requirement of energy than extended aeration capable of treating shock/toxic loads without affecting effluent quality, more

* Corresponding author.

economically efficient for smaller-sized plants, more adaptable to nutrient removal, providing higher quality effluent, and providing resistance to load variations without significantly affecting effluent quality [4]. Furthermore, due to the different dissolved oxygen (DO) levels within the channels of the Orbal reactor, nitrogen removal is much greater and more stable than in reactors with single-channel operations. Nevertheless, the limitations of an Orbal reactor include: a greater structure that requires greater space, lower food to microorganism (F/M) bulking, and the requirement of more aeration energy than completely mixed activated sludge system and plug-flow treatment [4]. Literature sources confirm the validity of chemical oxygen demand (COD) and nitrogen removal by methodologies of activated sludge within Orbal reactors [5–11]. It is noteworthy to investigate, more enhanced methodologies and suitable operating parameters to improve the treatment efficiency of wastewater treatment within an Orbal oxidation ditch. Literature sources have explored a diverse range of chemical, physical, and biological methods, including the process of magnetic field application.

In their review paper, Wang et al. [1] outlined the application of magnetic field on adsorption–separation of various influent mixed-liquor, including wastewater. This review was a consolidation of various research investigations to settle the effects of magnetic field application on adsorption–separation, bio-wastewater treatment, and advanced oxidation processes. In parallel with conventional wastewater treatment processes, the application of magnetic field displayed positive effects on adsorption–separation, bio-wastewater treatment, and advanced oxidation processes. The mechanisms of magnetic field-enhanced wastewater treatment have been thoroughly summarized from the standpoint of magnetic physiochemical and biological effects, such as magnetoresistance, Lorentz force, and intracellular radical pair mechanism. Likewise, in the review paper discussed by Zaidi et al. [12] which includes critical analysis regarding water magnetization and considers various applications that utilise magnetic field as an encouragement for wastewater treatment from various literature sources, it is established that magnetic field application enhances the performance of treatment systems. Literature sources reveal that the enhanced treatment performance is due to the impact on bacterial activity and physical properties of the particles for enhancement of precipitation, coagulation and sedimentation.

In the Orbal reactor, the process of nitrogen removal is activated by simultaneous nitrification and denitrification due to the alternations between the anoxic and aerobic zones along each of the channels [5]. Nitrification is the process in which ammonia continuously oxidizes to nitrite and further, oxidizes to nitrate. Nitrification is carried out mainly by two different groups of autotrophic nitrifying bacteria that create organic molecules by applying energy gained from inorganic sources (ammonia or nitrite). The first group, ammonia-oxidizing bacteria (AOB) gains energy by oxidizing ammonium and forms to nitrite. These are typically represented in wastewater treatment plants by two genera, Nitrosomonas and Nitrosospira. The second group, nitrite-oxidizing bacteria (NOB) are characterized by Nitrobacter and Nitrospira which oxidize nitrite to nitrate [13]. The standard design and operating approach within the reactor are to feed more oxygen to the outer channel than would be required to meet the complete requirements of oxygen demand. This is executed to enable the simultaneous process of nitrification and denitrification to occur in the outer channel. Within the outer channel of the Orbal reactor, the oxygen supplied enables nitrification to occur and the nitrate–nitrogen formed through nitrification is exhausted [14]. It is assumed that the heterotrophic microorganisms denitrify the nitrate–nitrogen created by the nitrifiers [6]. The volume of DO in the inner and middle channels, however, is much higher than the volume of DO in the outer channel, to fulfil the removal of the remaining nitrogen and organic matters from the outer channel [6]. Various literature sources confirm the positive influence of magnetic field application on the two different groups of autotrophic nitrifying bacteria communities (AOB and NOB) which result in enhancements in the reactor performance [15,16]. In the application of a static magnetic field on activated sludge, positive results were encountered regarding biomass growth, organic matter biodegradation, dehydrogenase action, and sludge reduction [17]. Ji et al. [18] investigated the effects of magnetic field application on the performance of activated sludge in wastewater treatment. The results attained by Ji et al. [18] indicated that the characteristic behaviours of activated sludge and organic pollutant biodegradation under the influence of a magnetic field were simulated, thus stemming an improvement in the performance of wastewater treatment. Under the influence of a magnetic field state, the biodegradation of organic compounds achieved a steady-state after 2 d. Within this study, magnetic field-enhanced wastewater treatment effects were proven, but as the magnetic field intensity increased substantially to 20 mT, results showed that the removal efficiency of organic compounds began to decrease. Yao et al. [15] established a magnetic carrier with a surface magnetic field, composed of hundreds of polyethylene terephthalate filaments. A 4mT magnetic field was applied to examine the enhanced magnetic bio-effects on nitrification and denitrification in sequencing batch biofilm reactors (SBBR). The experimenters established that the behaviours of ammonia and nitrite oxidation in the biofilm were enhanced within a magnetic carrier reactor compared to a non-magnetic carrier reactor. The specific oxygen uptake rate analysis study presented that nitrite and ammonia oxidation activities in the biofilm of the non-magnetic carrier reactor were 1.9 and 1.6 times lesser than those of the magnetic carrier reactor, respectively. This demonstrates the importance of magnetic field intensity and that increasing the magnetic field intensity does not necessarily mean that the removal efficiency of organic compounds will increase proportionally. In another study, Liu et al. [16] compared the conventional activated sludge and also the magnetic activated sludge processes (MAS) regarding the removal of pollutants. Results indicated that adding magnetic powder (Fe_3O_4) had no negative effect on the expansion of activated sludge. Furthermore, both processes had no significant modification in removing COD removal and the biochemical oxygen demand for five days (BOD_5). Unlike the conventional activated sludge process, the MAS process had greater removal efficiency in removing ammonium nitrogen (88.6% ± 7% removal). In this investigation, the average total nitrogen removal efficiency of both processes was

37.5% ± 14% and 42.3% ± 22%, respectively. Liu et al. [17] assessed the impact of adding magnetic powder within a sequencing batch reactor (SBR) on the microbial community, and also on the reactor performance. Results revealed that the magnetic SBR had 7.7% and 4.7% higher ammonia nitrogen and COD removal efficiencies compared with SBR without magnetic powder. This indicates that the application of the magnetic powder has enhancing wastewater treatment effects. The results obtained within this study also support the view that excessive increases in magnetic field intensity do not necessarily provide beneficial advantages in removal efficiencies, but can result in undesirable effects. While the biological effects of higher intensity magnetic fields, above 2 mT, have been relatively well studied by the majority of literature sources; fewer investigations have studied the effects of wastewater treatments with magnetic intensities, under 2 mT. Various methods of magnetic field application have been trialled by various sources to examine removal efficiency within activated sludge reactors. For all of these different applications, as well as enhancing effects on removal efficiencies, it is important to consider the economic justification, start-up and maintenance operations for viability with industrial applications.

This investigation aims to evaluate the application of a magnetic field to enhance and increase the removal efficiencies of wastewater within an Orbal reactor. During this study, an Orbal reactor was designed and built to conduct a pilot-scale experiment. The experiment examined and compared the effects, with and without magnetic field application on removal efficiencies and reactor performance. In this regard, concentrations of total nitrogen (TN), nitrate (NO_3^-), COD, BOD_5, sludge volume index (SVI), mixed liquor suspended solids (MLSS), mixed volatile liquor suspended solids (MVLSS), the ratio of food to microorganism (F/M) were analyzed, calculated, and results were compared. Comparisons were made with relevant literature examination to not only examine the viability of this method but to prove its cause for advancement and rivalry upon the performance properties of other existing methods. These performance properties were based on improved cost-efficiencies and simpler operations for set-up and maintenance.

2. Materials and methods

2.1. Set-up of the Orbal reactor

Upon undertaking research and review of various literature sources regarding the design of a typical pilot experimental design [19–22] to sample and examine the effects of magnetic field application on the removal efficiency of various wastewater pollutants, a laboratory-scale reactor was constructed. As shown in Fig. 1, the experimental pilot set-up of a typical Orbal reactor consists of three aeration channels and a sediment basin.

The dimensional characteristics of the tanks are presented in Table 1. The aeration reactor and settling tank were composed of a 2 mm thick steel sheet with an epoxy-paint coating. The total volume of the reactor was approximately 440 L. The total volume of the sedimentation basin was 88 L. To supply the influent sewage of the system, a tank with a capacity of 500 L was used and this tank was filled daily by the operator. Furthermore, for the constant inlet discharge rate to be maintained, a peristaltic pump with a power consumption of 410 W was used to transfer the wastewater from the tank to the reactor. If the inlet supply tank was located above the liquid surface without the power consumption, it would have been under the force of gravity and so, the rate of flow of the inlet discharge would have encountered approximately 50% variation from when the minimal liquid was in the supply tank in comparison to when the tank supply was full. Sewage entered the external channel through the inlet pipe, which was located 50 cm below the liquid surface. The sewage entered below the liquid to enable sufficient mixing, and so that the microorganisms within the channels were well-fed.

To find the optimum retention time for the reactor, four different hydraulic retention times were set to 16, 20, 24 and 31 h and were analyzed. In relation to each retention time and the total volume of the reactor, the input flow rates were fixed at 26, 22, 18 and 14 L/h, respectively.

2.2. Operation of reactor start-up

Diffuser discs were installed at the bottom of the aeration channels. There were four aeration units in the outer channel, three aeration units in the middle channels and three aeration discs in the inner channel. The airflow of each aeration unit was maintained in a uniform manner during the experiment by controlling the valve and gas flowmeter and only changed due to oxygen demand (DO) changes. During the study, the DO concentration of each channel was measured daily using a portable DO meter. All three channels (outer, middle, and inner) were anaerobic tanks with DO concentrations of 0.4 ± 0.1, 0.9 ± 0.2 and 2.6 ± 0.5 mg/L, respectively. It is also important to note, that the ambient temperature of the pilot site was maintained at 24°C during the test, whereby the water temperature was kept at approximately 22°C.

2.3. Feeding and seeding

At the beginning of the system start-up, 100 L of activated sludge was added. The system operated in batch mode for 5 d, during which feed was added manually. From the sixth day, each consecutively, an inlet flow of 14, 18, 22, and 26 L/d, entered the reactor to determine the optimum retention time. The obtained optimal retention time was then used within the proceedings of the experiment.

In this investigation, the influent wastewater was synthetic. The synthetic wastewater was composed of tap water, sugar beet molasses and urea fertilizer. It should be noted that the sugar beet molasses was used to supply COD and BOD_5, however, to supply the input of TN, urea fertilizer was used. Hence, the pollutants of the influent water in this experimental procedure did not include any other basis of concentrations or matters. The characteristics and values of the influent wastewater during the investigation period are summarized in Table 2.

2.4. Preparation of magnetic field

To investigate the effects of magnetic field application on the performance of pollutant removal efficiency within

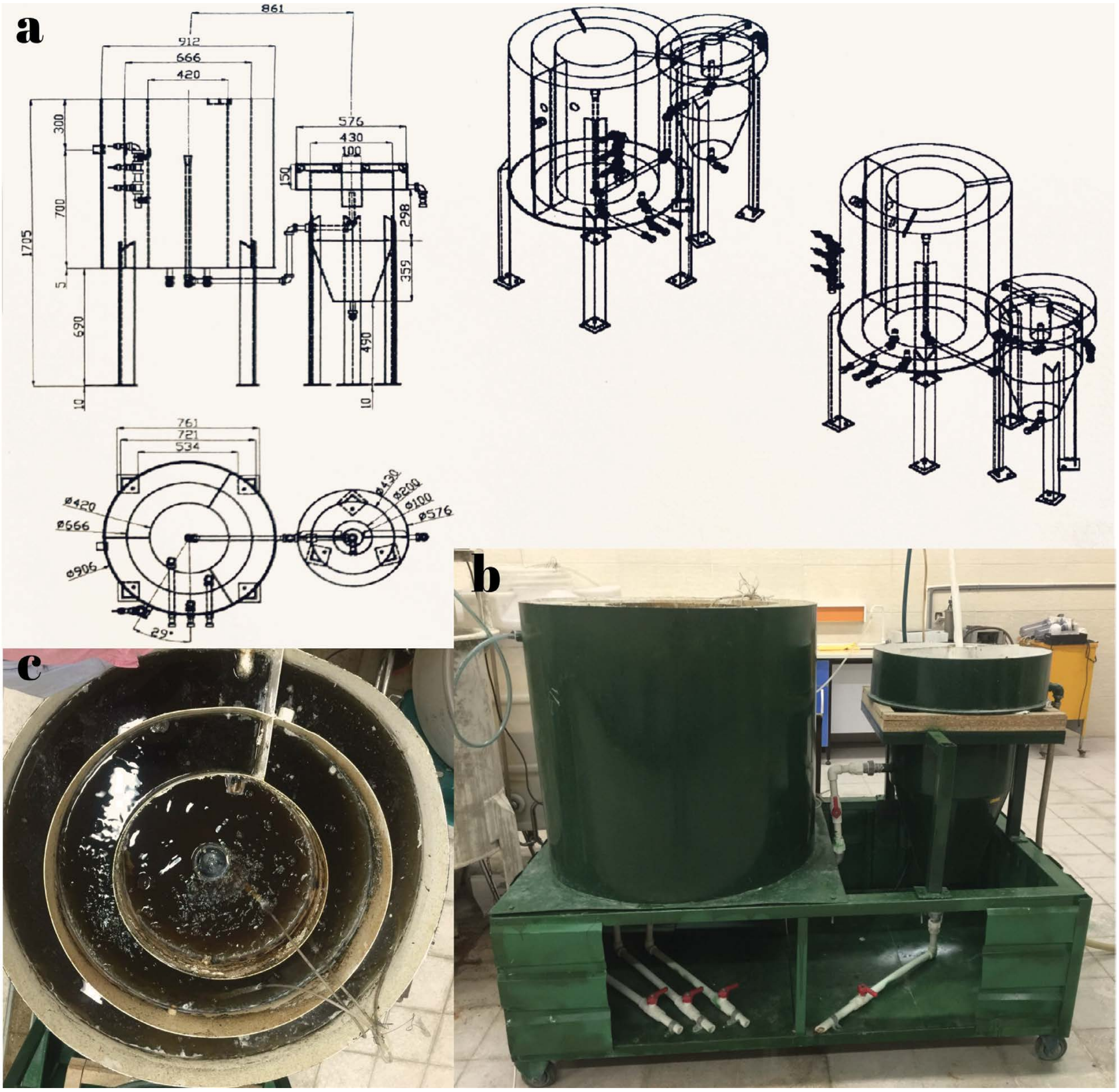

Fig. 1. Illustration of Orbal pilot: (a) Schematic diagram of the Orbal reactor. (b) Illustration of the experimental set-up after construction from the front view. (c) Illustration of the experimental set-up upon operation from the top view.

Table 1
Presents the dimensional characteristics of each of the three channels within the Orbal reactor

Channel	Hydraulic retention time (h)	Volume (L)	Cross-sectional area (m^2)	High (mm)	Diameter (mm)
Outer	9.2	200	0.29	700	900
Middle	6.6	145	0.21	700	660
Inner	4.2	95	0.14	700	420

an Orbal reactor, two magnetic fields of 1.3 and 2 mT were prepared. For this purpose, 100 neodymium magnets were used in both trials. The dimensions of the 1.3 and 2 mT magnets in the fields were 4 mm × 40 mm × 10 mm and 8 mm × 40 mm × 12 mm, respectively. Before this set-up, an approximate range for the applied intensities was known, but the exact intensity values were recognized after placing the magnets in appropriate positions. These magnets were distributed homogeneously on the inner surface of the channels at approximately equal intervals. The exact magnetic intensity values were estimated using a portable field strength measurement system (Hi-3604 Esco Technology Company).

Compared to other magnetic treatment systems, the methodology used to prepare the magnetic field and the operations after application used within this study is deemed more economically and environmentally efficient.

2.5. Analytical methods

During a 156-d period, every day except for holidays and national holidays, the effluent of the system was transferred to the laboratory and sampled for analysis. Additionally, taking into consideration the flow rate and volume of the influent supply tank, sampling was performed from the reactor input on an every-other day basis at the time of filling the influent supply tank. The value of the COD and BOD_5 was determined according to Standard Methods [23]. To measure the values for MLSS and MVLSS, a well-mixed sample was filtered through a 0.45 micro-filter. The concentrations of TN and nitrate were analyzed employing the digestion method using a DR6000 Spectrophotometer, Hach. The measurement of the sludge volume, after 30 min of settling (SVI) was used to describe the sedimentation performance of sludge. DO was determined using a portable DO meter (HQ30D, Hach).

3. Results and discussion

3.1. Determination of the optimum retention time

Four distinctive retention times were utilized initially to determine the optimum retention time of the experimental procedures. It should be noted that for each retention time, each over a 20-d period, the influent and effluent (BOD_5) values were measured every day. According to Fig. 2, the retention time of 22 h shows to have the maximum efficiency relative to the three other retention times. As a means to operate with the optimum efficiency for removal, this value for the optimum retention time was

Table 2
Displays the mean and min.-max. values of the pollutants within the influent wastewater of the experimental set-up

Parameter	Mean	Min. to max.
BOD_5	281	270–294
COD (mg/L)	511	491–550
TN (mg/L)	32.17	30–34.10
TP (mg/L)	5	4–6
T (°C)	24	23–25

Values are the average ± standard deviations.

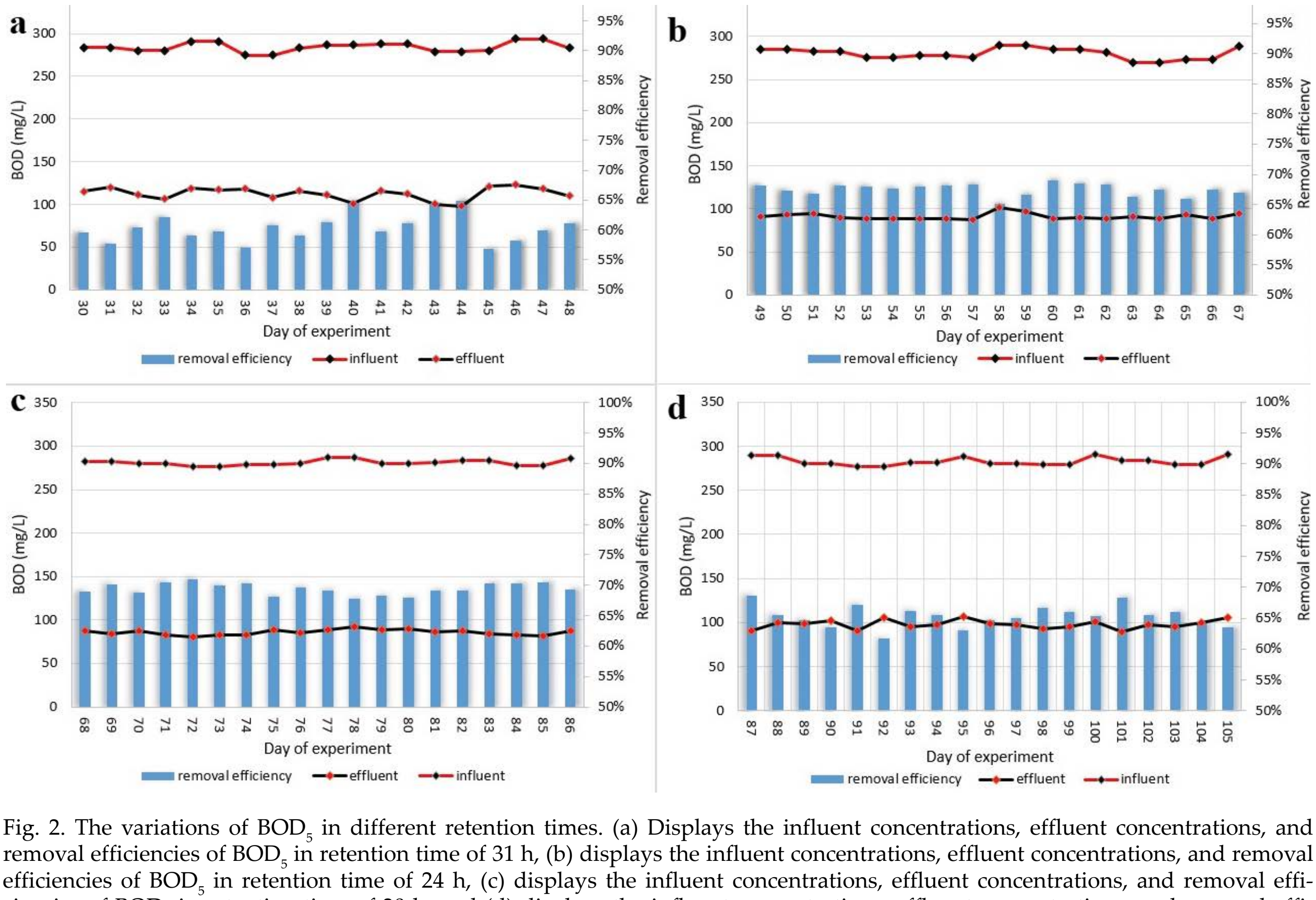

Fig. 2. The variations of BOD_5 in different retention times. (a) Displays the influent concentrations, effluent concentrations, and removal efficiencies of BOD_5 in retention time of 31 h, (b) displays the influent concentrations, effluent concentrations, and removal efficiencies of BOD_5 in retention time of 24 h, (c) displays the influent concentrations, effluent concentrations, and removal efficiencies of BOD_5 in retention time of 20 h, and (d) displays the influent concentrations, effluent concentrations, and removal efficiencies of BOD_5 in retention time of 16 h.

implemented throughout the operations of the experimental investigation.

3.2. Reactor performance in traditional Orbal oxidation ditch

Fig. 3a–c show the removal performance of BOD_5, COD and TN in the Orbal reactor without a magnetic field, with a water temperature of 22°C ± 1°C. Furthermore, it took approximately 29 d for the system to achieve a steady state and in this period, only the concentrations of DO and BOD_5 were checked. In this study, only upon reaching a steady state, results were considered. After reaching a steady state in the reactor and implementing the optimum retention time, the concentrations of TN and nitrate were analyzed. Furthermore, to evaluate the sedimentation performance of sludge, the SVI index was checked daily (Fig. 3d). In addition, Fig. 4e shows the amount of nitrate in the effluent without the application of a magnetic field. It should be noted that 19 samples were taken during this time interval (on working days). TN in the effluent was approximately 10.7 mg/L and TN removal was incomplete, with a removal efficiency of 66.3%. The BOD_5 and COD removal efficiencies were 69% and 70.4% respectively, and the average BOD_5 and COD in the effluent were approximately 86 and 156 mg/L. The TN and COD removal performance were not sufficient. Furthermore, nitrate in the effluent was approximately 27.5 mg/L. SVI factor stands between 85 to 100 with an average of 94.73.

3.3. Reactor performance Orbal oxidation ditch with magnetic field

30 samples were taken over a period of 30 working days. The first 15 samples were taken under the application of a 1.3 mT magnetic field, and the second set of 15 samples was taken under the application of a 2 mT magnetic field. Fig. 4a–c show the removal performance of BOD_5, COD and TN in the Orbal reactor under the application of a magnetic field, respectively. Furthermore, the average SVI factor in the reactor is shown in Fig. 4d. The change in nitrate along the biological system is illustrated in Fig. 4e for each day.

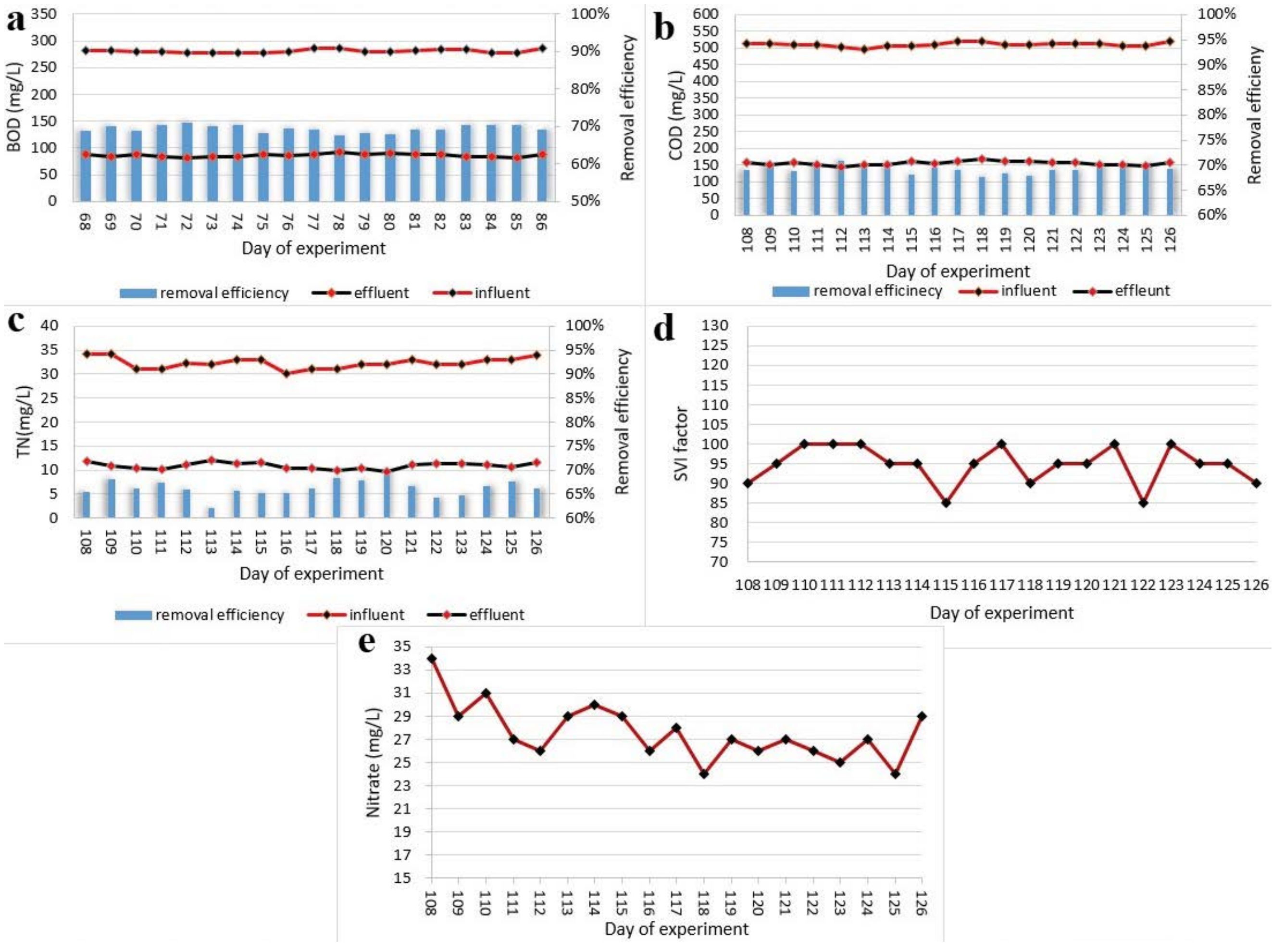

Fig. 3. The variations of BOD_5, COD, TN, nitrate and average SVI in channels with the time before using magnetic field: (a) the influent concentrations, effluent concentrations, and removal efficiencies of BOD_5, (b) the influent concentrations, effluent concentrations, and removal efficiencies of COD, (c) the influent concentrations, effluent concentrations, and removal efficiencies of TN, (d) SVI factor in the reactor and (e) the effluent concentrations of nitrate.

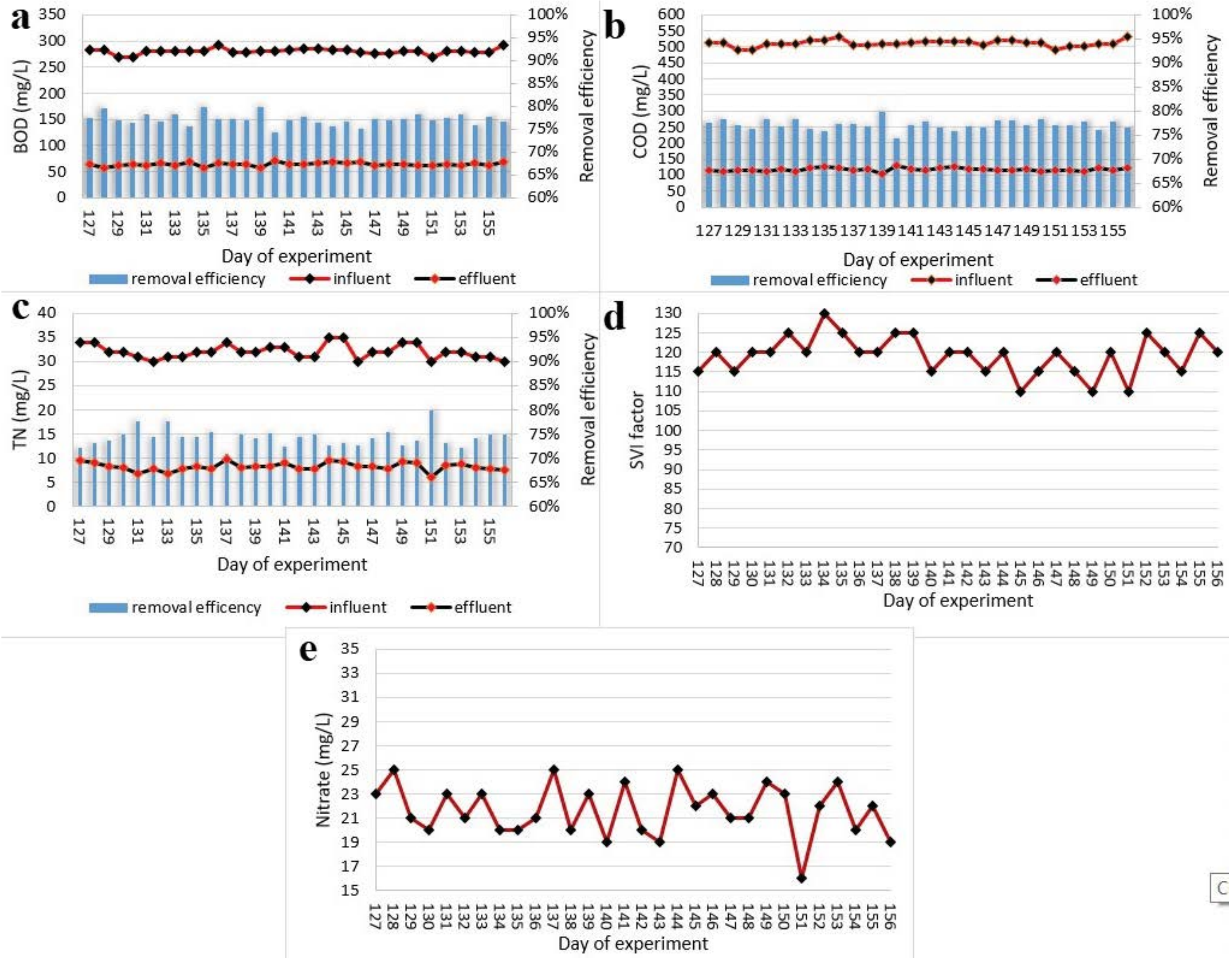

Fig. 4. Graphs displaying the variations of BOD_5, COD, TN, nitrate and SVI with the time after a magnetic field application. Graph illustrating the influent concentrations, effluent concentrations, and removal efficiencies of (a) BOD_5, (b) COD (c) TN, (d) graph illustrating the SVI factor in the reactor and (e) graph illustrating the concentration of nitrate in the effluent.

TN in the effluent was approximated at 8.26 and 8.28 mg/L, with removal efficiencies of approximately 77.4% and 77.2%, under the influence of the magnetic intensities 1.3 and 2 mT, respectively. BOD_5 in the effluent was approximately 63 and 65 mg/L, with removal efficiencies of approximately 77.4% and 77%. COD in the effluent was approximately 116.9 and 117.2 mg/L, with removal efficiencies of approximately 76.1% and 76.2%. Upon the magnet field application, the nitrate concentration in effluent had decreased by 21%. The results indicate that the application of a magnetic field significantly enhances the removal of nitrogen, nitrate, BOD_5 and COD. It must be mentioned, however, that applying a higher magnetic intensity does not necessarily have an enhanced influence on the removal of the above-mentioned pollutants. A minor difference in the removal efficiencies can be observed when analyzing the two intensities. SVI factor ranges between 110 to 130 with an average of 116 and 117 under the magnetic fields of 1.3 and 2mT. This indicates an increase in the amount of activated sludge and its growth rate upon application of a magnetic field. Again, regarding the influence of increased magnetic intensities, the results indicate that a higher magnetic intensity does not necessarily result in proportionally higher results.

3.4. Mechanisms of magnetic effects on wastewater treatment

3.4.1. Physico-chemical effects of magnetic field on wastewater treatment

As a physical strategy, the presence of a magnetic field has critical physico-chemical effects due to its magnetic interaction with electrons or particles of pollutants in wastewater. Thus, magnetic field application does not only provide significant enhancements in the expulsion productivity of contaminants in wastewater but also provides a new way to reuse attractive adsorbents and catalysts during wastewater treatment processes. In this portion, magnetization impact and magnetization of water are explored.

3.4.1.1. Magnetization effect

By altering the electrokinetic potential of charged particles, the application of the magnetic field contributes to the modification of atomic structure, conductivity, and polarization [24]. The modifications made to the electrokinetic potential thus promotes the rearrangement of charged particles. In summary, due to the atomic improvement, magnetic field application has the potential to promote granulation [25], sedimentation of activated sludge and particles and pollutants removal.

3.4.1.2. Magnetization of water

Furthermore, the electrokinetic potential reduction of water triggered by magnetic field application has the potential to enhance the rapid coagulation of particles [26]. Moreover, the effects of magnetic field application results in alterations of hydrogen bonds between water molecules, which supplement the reactions in water such as adsorption enhancement [27].

3.4.2. Biological effects of magnetic field in wastewater treatment

3.4.2.1. Cell membrane

The maximum removal of COD is achieved by the enhanced relative hydrophobicity and reduced membrane negative charge which is sought to occur upon magnetic field application [1]. Upon magnetic field application, re-arrangements are not only made to the coordination of the membrane phospholipid fatty acid [28], but modifications are also made to cell shape, surface hydrophobicity, and cell membrane potentials [29] which affect membrane fluidity and cell metabolism.

3.4.2.2. Enzyme activity

For the most part, the application of magnetic field stimulates the enzyme activity [28] such as enhancing the action of dehydrogenase [30]. magnetic field application can alter chemicals action by: modification in the molecular compositions of the enzymes by means of hindering the extending vibration in some chemical bonds, counting auxiliary structure and tertiary structure of pertinent proteins, for example, under the influence of a magnetic intensity of 0.0018 T [31]; influencing the electronic energy level switch of metal particles as coenzymes which brought about the disparity of enzyme-catalyzed response rate [32]; changing the dynamic energy of unpaired electrons found at the catalytic movement center of enzymes [33]; and affecting the electron transport in enzyme-catalyzed response and forming a more dynamic enzyme adaptation [31].

3.4.2.3. Intracellular radial pair mechanism

In ion radical mechanism of DNA union, magnetic field can influence the movement of β-polymerase movement, which is known to attain DNA replication by incorporating nucleotides into DNA strands [34].

3.5. Biomass concentrations change in activated sludge under the presence of a magnetic field

The MLSS and mixed liquor volatile suspended solid (MLVSS) are used as an indication of the microorganism's community presence. Fig. 5 shows the MLSS and MLVSS of the reactor throughout the investigation (application of the magnetic field on the Orbal reactor is illustrated by yellow line on the chart).

Fig. 5a shows that the quantity of MLSS in the outer channel is higher than in the middle channel due to the anoxic conditions. MLSS in the middle channel is higher than in the inner channel due to the lower aeration rate in the inner channel. Therefore, MLSS is inversely related to the DO concentration within the Orbal reactor. Since MLVSS follows similar characteristics as MLSS in well-functioning systems, graphs and illustrations follow similar characteristics and patterns. It is rather significant to mention that upon application of the magnetic field in the Orbal reactor, the rates of MLSS and MLVSS increased profoundly. The average MLSS and MLVSS values for the samples and the corresponding fluctuation percentages in the system are

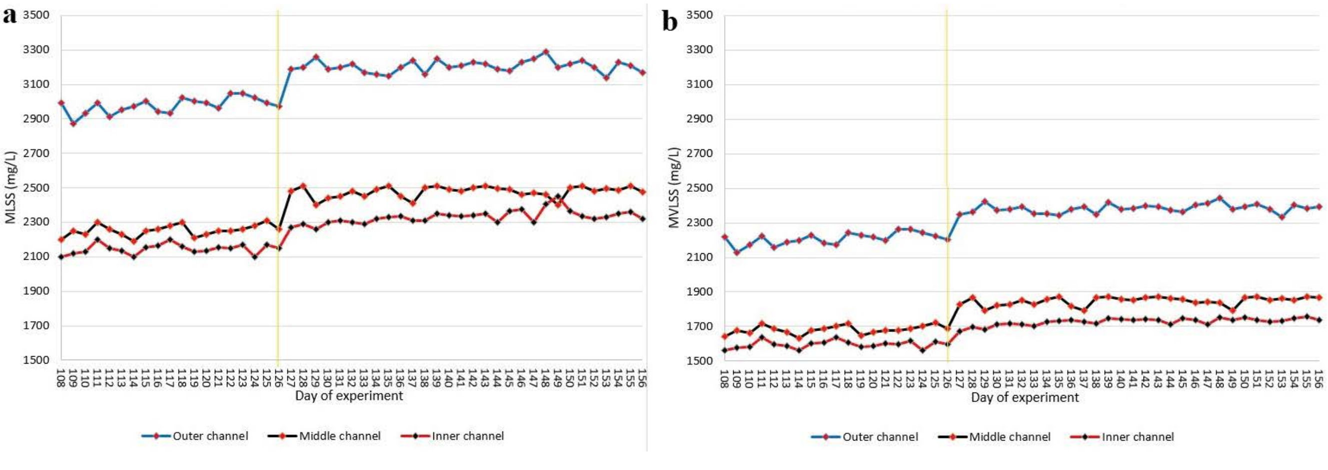

Fig. 5. Graph displaying the variations of MLSS and MLVSS prior to and after the application of a magnetic field to the Orbal reactor: (a) Illustration of the MLSS within the inner, middle and outer channels and (b) illustration of the MLVSS in inner, middle and outer channels.

displayed and presented in Table 3. The results indicate that the application of a magnetic field has a significantly positive effect on the growth of the activated sludge. This observable effect is supported and reasoned by the previous section describing the biological effects of magnetic field in wastewater treatment. The same phenomenon has previously been reported by Ying et al. [35], who detected that the concentration of MLSS and MVLSS improved when using a magnetic field on activated sludge processes. It should also be noted that minor to no changes were observed when comparing the effects of different magnetic field intensities.

As the sludge concentration increases, the sludge loading ratio decreases. For each of the three channels, before and after the application of the magnetic field, the F/M ratio of the experiment is shown in Table 4.

F/M ratio is a significant parameter for the selection of nitrifying autotrophs. It is suggested that the F/M ratio should be kept under 0.4 COD/VSS to attain steady nitrification and removal of TN [36]. According to Kumar et al. [37], lower F/M ratios suppress the heterotrophic organism's growth in the reactor because of the lack of sufficient organic carbon. Generally, nitrifying autotrophs are transferred to those areas where the growth of heterotrophic is limited. Consequently, the lowered F/M ratios express the fondness for nitrifying autotrophs in comparison with the heterotrophic organism [14].

3.6. DO concentration

Nitrogen removal performance in the Orbal reactor is mainly affected by simultaneous nitrification and denitrification processes. DO significantly influences the dynamic balance between nitrification and denitrification rates in the outer channel Fig. 6 shows the concentrations of DO within the channels of the reactor. Furthermore, the application of a magnetic field is shown by the yellow line on the chart. As mentioned, the concentration of DO is the main factor affecting nitrification and denitrification, thus, the distribution of DO in the traditional and magnetic Orbal oxidation ditch were analyzed.

The airflow of each aeration unit was maintained during the study by controlling the valve and gas flowmeter and only changed as needed due to oxygen demand (DO) changes. During the study, the DO of each channel was measured daily by a portable DO meter. The outer channel was an anaerobic tank with an average DO of 0.38 mg/L, the inner channel had a DO of 2.65 mg/L, and the DO of the middle channel average was 0.93. It is noteworthy to mention that on the 125th day of the experiment (3 d after the application of the magnetic field), the DO level had significantly decreased. In the outer channel, DO levels had reduced by 38% compared to the previous sample, which did not include a magnetic field application. Furthermore, in the middle channel and inner channels, DO concentration had decreased by 37% and 26%, respectively. For this reason, the amount of oxygen entering through the aeration disk was increased to return the oxygen level to its previous state by fluctuations in the valve and gas flowmeter. This indicates that, after the application of the magnetic field, the growth of activated sludge and bacteria increased and as a result, their oxygen demand increased. Also, after increasing the intensity of the magnetic field from 1.3 mT to 2 mT, no significant changes in the amount of DO were observed.

3.7. Comparison with relative studies and literature sources

The aim of this section is to compare and contrast the study's findings with other relevant research to support the significance of the obtained results, regarding the topic of applying a magnetic field to an activated sludge reactor for enhancements of pollutant removal. Table 5 presents four different studies (including this study), all undertaken by different experimenters using four different experimental methods, to provide more valid and reliable evaluations of wastewater pollutant removal efficiencies upon the application of a magnetic field. Table 5 presents: the activated sludge method used; the application method of magnetic

Table 3
Table displaying the average values for the MLSS and MLVSS within the reactor before and after the application of a magnetic field

Channel	MLSS (mg/L) (without magnetic field)	MLSS (mg/L) (with magnetic field)	Fluctuation (%)	MLVSS (mg/L) (without magnetic field)	MLVSS (mg/L) (with magnetic field)	Fluctuation (%)
Outer	2,975	3,210	+8%	2,210	2,390	+8%
Middle	2,252	2,475	+10%	1,678	1,852	+10%
Inner	2,145	2,330	+9%	1,593	1,736	+9%

Table 4
Displaying the F/M values of the reactor before and after the application of a magnetic field

Channel	F/M (kg·BOD_5/kg·MLVSS·d) (without magnetic field)	F/M (kg·BOD_5/kg·MLVSS·d) (with magnetic field)	Fluctuation (%)
Outer	0.23	0.2	–12%
Middle	0.4	0.34	–14%
Inner	0.47	0.4	–14%

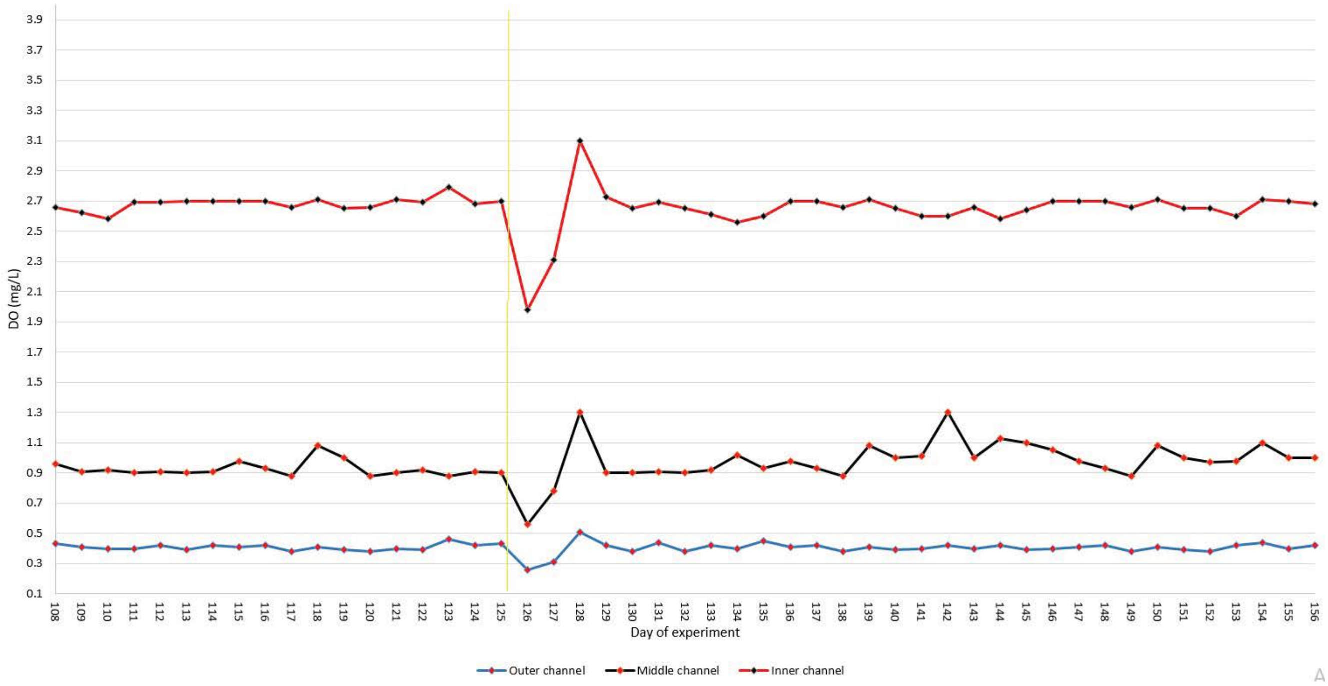

Fig. 6. DO concentration in inner, middle and outer channels.

Table 5
Displaying the activated sludge method and related information of the investigation under consideration and comparable studies conducted previously

Study	Activated sludge method	Applying magnetic field method	Improvements in nitrogen removal	Improvements in COD removal	Improvements in nitrate removal	F/M ratio
This Study	Orbal reactor	Static field with several magnets	11%	6%	21%	–15%
[16]	Conventional activated sludge	Magnetic powder	16%	2%	Not applicable	–35%
[15]	Sequencing batch biofilm reactors	Surface magnetic field	8%	Not applicable	6%	Not applicable
[38]	Sequencing batch reactor	Magnetic nanoparticles	17%	Not applicable	15%	Not applicable

Percentages are written to some extent and their decimals and deviations are ignored.

field; the improvements in nitrogen removal, COD removal, and nitrate removal; and the F/M ratio. As shown in Table 5, the results of this investigation are rather acceptable when compared with similar studies. In regards to improvements in nitrogen removal, the results obtained in this study are approximate to the average of the results obtained by the other experiments. Furthermore, in relation to improvements in COD removal, only one other study has examined this subject. According to these findings, the removal efficiency of COD, using the Orbal reactor with the application of static field by several magnets, is greater than the other method. Furthermore, the nitrate removal efficiency in this study is significantly higher compared to others. The more significant element regarding this experimental methodology is relevant to the preparation of the magnetic field. Comparatively, this specific method is associated with greater cost-efficiencies, enhanced accessibility, and simpler maintenance and operation. For instance, with the application of magnetic powder, the substance has to be regularly supplemented to the reactor which increases costs and maintenance to uphold a stable magnetic field. Within the application used within this research methodology, however, once the magnets have been initially applied, a stable magnetic field is maintained for a long duration without the requirement of any additional supplementations.

3.8. Study limitation

There are also limitations that need to be considered when implementing a magnetic field within a wastewater treatment system. As for practical applications, exposure intensity is the most important aspect to consider. The most common strength range for degradation of contaminants in the presence of bacteria or microorganisms is 1 mT to 1 T [1]. Higher magnetic field strengths can in some circumstances, stop bacterial activity and have an adverse effect on treatment performances. Specific strength level knowledge may support this. However, specific understanding for the growth rate of certain bacteria/microbes is still limited. Each bacterium has a unique sensitivity to magnetic field strength, where some can grow under stronger magnetic fields, while others can only be maintained at lower intensities. Different types of bacteria/microbes play an important role in the treatment process, and their presence in the wastewater can lead to the requirement of further research as their characteristics may adversely affect the treatment system.

Within the proceedings of this research, budget limitations were, also incurred. There were no funds supplied by any academic or industrial organizations and the costs incurred were limited to be supplied by individual funds. Due to the expensive costs of magnets, it was only possible to supply two different magnetic intensities.

4. Conclusion

The application of a magnetic field significantly improved the performance of pollutant removal efficiency within an Orbal reactor, and also increased the biomass concentration. Regarding the removal efficiency of TN, nitrate, COD and BOD_5, the magnetic activated sludge process indicated significant improvements. In comparison to conventional Orbal oxidation ditch methods, the nitrification performance was increased and enhanced. The increased MLVSS led to an average 14% decrease in the F/M ratio within the three channels of the Orbal reactor. The reduced F/M ratio uncovered the preference for nitrifying autotrophs in comparison with the heterotrophic organism.

With sufficient evidence from this research and other relevant literature confirming the positive influence of a magnetic field on the activated sludge process, the removal efficiency of pollutants in wastewater was significantly improved with magnetic field application. However, these sources do not provide sufficient insight into obtaining the optimal removal efficiency when applying a magnetic field.

It should be recommended that in further research, as well as trialing a higher number of various magnetic intensities to find the optimal magnetic intensity required to achieve the optimal removal efficiency, unstatic and dynamic magnetic fields should also be investigated. Furthermore, it should be noted that the utilization of neodymium magnets could be replaced with the use of magnetic coils. In terms of operations at the semi-industrial level, the applications of a periodic electromagnetic coil for activated sludge can be created by recirculation through a separate column surrounded by an electromagnetic coil. To determine the most efficient methodology for providing the utmost enhancement of wastewater biodegradation, a thorough economic and environmental analysis should be undertaken. For each methodology, an examination of operating costs, start-up requirements and power requirements should be carried out. Comparisons of these factors should be made between a number of the most efficiently-known applications to determine the most economically and environmentally viable application.

Acknowledgements

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

[1] Y. Wang, X. Gu, J. Quan, G. Xing, L. Yang, Ch. Zhao, P. Wu, F. Zhao, B. Hu, Y. Hu, Application of magnetic fields to wastewater treatment and its mechanisms: a review, Sci. Total Environ., 773 (2021) 145476, doi: 10.1016/j.scitotenv.2021.145476.
[2] E. Gogina, I. Gulshin, Characteristics of low-oxygen oxidation ditch with improved nitrogen removal, Water, 13 (2021) 3603, doi: 10.3390/w13243603.
[3] Y. Qiu, C. Zhang, B. Li, J. Li, X. Zhang, Y. Liu, P. Liang, X. Huang, Optimal surface aeration control in full-scale oxidation ditches through energy consumption analysis, Water, 10 (2018) 945, doi: 10.3390/w10070945.
[4] L. Metcalf, H.P. Eddy, Wastewater Engineering: Treatment and Reuse, 4th ed., McGraw-Hill, New York, 2003.
[5] X. Hao, H.J. Doddema, J.W. van Groenestijn, Conditions and mechanisms affecting simultaneous nitrification and denitrification in a Pasveer oxidation ditch, Bioresour. Technol., 59 (1997) 207–215.
[6] H.-D. Park, J.M. Regan, D.R. Noguera, Molecular analysis of ammonia-oxidizing bacterial populations in aerated-anoxic Orbal processes, Water Sci. Technol., 46 (2002) 273–280.
[7] R.J.L.C. Drews, A.M. Greeff, Nitrogen elimination by rapid alternation of aerobic/"anoxic" conditions in "Orbal" activated sludge plants, Water Res., 7 (1973) 1183–1194.
[8] X. Zhou, X. Guo, Y. Han, J. Liu, J. Ren, Y. Wang, Y. Guo, Enhancing nitrogen removal in an Orbal oxidation ditch by optimization of oxygen supply: practice in a full-scale municipal wastewater treatment plant, Bioprocess. Biosyst. Eng., 35 (2012) 1097–1105.
[9] Q. Yong, Z. Chi, L. Bing, L. Ji, Z. Xiaoyuan, L. Yanchen, L. Peng, H. Xia, Optimal surface aeration control in full-scale oxidation ditches through energy consumption analysis, Water, 10 (2018) 945, doi: 10.3390/w10070945.
[10] X. Wang, T. Chen, P. Jin, A. Zhang, C. Gao, X. Qi, Y. Zhang, Enhanced total nitrogen removal performance in a full scale Orbal oxidation ditch by a novel step aeration mode, Bioresour. Technol., 294 (2019) 122228, doi: 10.1016/j.biortech.2019.122228.
[11] X. Wang, C. Gao, P. Jin, Y. Zhang, Y. Xie, T. Chen, A. Zhang, Nitrogen removal performance and bacterial community in a full-scale modified Orbal oxidation ditch with internal nitrate recycle and biocarriers, J. Water Process Eng., 40 (2021) 101791, doi: 10.1016/j.jwpe.2020.101791.
[12] N. Syamimi Zaidi, J. Sohaili, K. Muda, M. Sillanpää, Magnetic field application and its potential in water and wastewater treatment systems, Sep. Purif. Rev., 43 (2014) 206–240.
[13] Q. Cao, X. Li, H. Jiang, H. Wu, Z. Xie, X. Zhang, N. Li, X. Huang, Z. Li, X. Liu, D. Li, Ammonia removal through combined methane oxidation and nitrification-denitrification and the interactions among functional microorganisms, Water Res., 188 (2021) 116555, doi: 10.1016/j.watres.2020.116555.
[14] K.C.D. Agbewornu, T.M. Adyel, J. Zhai, Optimizing nitrogen removal in a hybrid oxidation ditch, J. Environ. Chem. Eng., 9 (2021) 105443, doi: 10.1016/j.jece.2021.105443.
[15] C. Yao, H.-Y. Lei, Q. Yu, S.-P. Li, H.-L. Li, K. Chen, X.-H. Zhang, Application of magnetic enhanced bio-effect on nitrification: a comparative study of magnetic and non-magnetic carriers, Water Sci. Technol., 67 (2013) 1280–1287.

[16] Z.M. Liu, Z. Liang, S.G. Wu, F. Liu, Treatment of municipal wastewater by a magnetic activated sludge device, Desal. Water Treat., 53 (2015) 909–918.

[17] Y. Liu, J. Li, W. Guo, H. Ngo, J. Hu, M.T. Gao, Use of magnetic powder to effectively improve the performance of sequencing batch reactors (SBRs) in municipal wastewater treatment, Bioresour. Technol., 148 (2017) 135–139.

[18] Y. Ji, Y. Wang, J. Sun, T. Yan, J. Li, T. Zhao, X. Yin, C. Sun, Enhancement of biological treatment of wastewater by magnetic field, Bioresour. Technol., 101 (2010) 8535–8540.

[19] J.L. Zilles, J. Peccia, D.R. Noguera, Microbiology of enhanced biological phosphorus removal in aerated—anoxic Orbal processes, Water Environ. Res., 74 (2002) 428–436.

[20] S.Y. Gao, Y.Z. Peng, S.Y. Wang, J. Yan, Novel strategy of nitrogen removal from domestic wastewater using pilot Orbal oxidation ditch, J. Environ. Sci., 18 (2006) 833–839.

[21] L. Lin, G. Min, L. Junxin, Distribution characterization of microbial aerosols emitted from a wastewater treatment plant using the Orbal oxidation ditch process, Process Biochem., 46 (2011) 910–915.

[22] X. Wang, T. Chen, P. Jin, A. Zhang, C. Gao, X. Qi, Y. Zhang, Enhanced total nitrogen removal performance in a full scale Orbal oxidation ditch by a novel step aeration mode, Bioresour. Technol., 294 (2019) 122228, doi: 10.1016/j.biortech.2019.122228.

[23] Standard Methods for the Examination of Water and Wastewater, 23rd ed., American Water Works Association, Washington D.C., USA, 2017.

[24] M. Zielinski, P. Rusanowska, M. Debowski, A. Hajduk, Influence of static magnetic field on sludge properties, Sci. Total Environ., 625 (2018) 738–742.

[25] X.H. Wang, M.H. Diao, Y. Yang, Y.J. Shi, M.M. Gao, S.G. Wang, Enhanced aerobic nitrifying granulation by static magnetic field, Bioresour. Technol., 110 (2012) 105–110.

[26] N. Gokon, A. Shimada, H. Kaneko, Y. Tamaura, K. Ito, T. Ohara, Magnetic coagulation and reaction rate for the aqueous ferrite formation reaction, J. Magn. Magn. Mater., 238 (2002) 47–55.

[27] J. Ma, Y. Ma, F. Yu, A novel one-pot route for large-scale synthesis of novel magnetic CNTs/Fe@C hybrids and their applications for binary dye removal, ACS Sustainable Chem. Eng., 6 (2018) 8178–8191.

[28] L. Tan, Y.F Shao, G.D. Mu, S.X. Ning, S.N. Shi, Enhanced azo dye biodegradation performance and halotolerance of *Candida tropicalis* SYF-1 by static magnetic field (SMF), Bioresour. Technol., 295 (2020) 122283, doi: 10.1016/j.biortech.2019.122283.

[29] Q. Hu, R.P. Joshi, D. Miklavcic, Calculations of cell transmembrane voltage induced by time-varying magnetic fields, IEEE Trans. Plasma Sci., 48 (2020) 1088–1095.

[30] M. Łebkowska, A. Rutkowska-Narozniak, E. Pajor, A. Tabernacka, M. Załęska-Radziwiłł, Impact of a static magnetic field on biodegradation of wastewater compounds and bacteria recombination, Environ. Sci. Pollut. Res., 25 (2018) 22571–22583.

[31] F.C. Fraga, A. Valério, V.A. de Oliveira, M. di Luccio, D. de Oliveira, Effect of magnetic field on the Eversa® Transform 2.0 enzyme: enzymatic activity and structural conformation, Int. J. Biol. Macromol., 122 (2019) 653–658.

[32] P. Logeshwaran, K. Krishnan, R. Naidu, M. Megharaj, Purification and characterization of a novel fenamiphos hydrolysing enzyme from *Microbacterium esteraromaticum* MM1, Chemosphere, 252 (2020) 126549, doi: 10.1016/j.chemosphere.2020.126549.

[33] A. Wasak, R. Drozd, D. Jankowiak, R. Rakoczy, Rotating magnetic field as tool for enhancing enzymes properties - laccase case study, Sci. Rep., 9 (2019) 3707, doi: 10.1038/s41598-019-39198-y.

[34] U.G. Letuta, V.L. Berdinskiy, Biological effects of static magnetic fields and zinc isotopeson *E. coli* bacteria, Bioelectromagnetics, 40 (2019) 62–73.

[35] C. Ying, K. Umetsu, Y. Sakai, I. Ihara, T. Yamashiro, Milking parlour wastewater treatment by magnetic activated sludge process, S.A.S.J., 39 (2009) 1–6.

[36] Y.J. Wu, L.M. Whang, M.Y. Chang, T. Fukushima, Y.C. Lee, S.S. Cheng, S.F. Hsu, C.H. Chang, W. Shen, C.Y. Yang, R. Fu, Impact of food to microorganism (F/M) ratio and colloidal chemical oxygen demand on nitrification performance of a full-scale membrane bioreactor treating thin transistor liquid crystal display wastewater, Bioresour. Technol., 141 (2013) 35–40.

[37] M. Kumar, P.Y. Lee, T. Fukusihma, L.M. Whang, J.G. Lin, Effect of supplementary carbon addition in the treatment of low C/N high-technology industrial wastewater by MBR, Bioresour. Technol., 113 (2012) 148–153.

[38] S.Q. Ni, J. Ni, N. Yang, J. Wang, Effect of magnetic nanoparticles on the performance of activated sludge treatment system, Bioresour. Technol., 143 (2013) 555–561.