Electromagnetic Fields for the Treatments of Wastewater: A Review of Applications and Future Opportunities

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Electromagnetic fields (EMFs) for water and wastewater treatments show promising potentials. Safety, compatibility and simplicity, environmentally friendliness, low operating cost and not proven harmful effects are the main advantages of EMFs over conventional methods for wastewater treatment. In addition to the antimicrobial and antibacterial effects of EMFs on wastewater, these fields have special properties useful for wastewater treatment process: modifying the physical and chemical properties of water molecules and other elements, sludge precipitation, phosphorus and organic compounds removal from wastewater are some of these characteristics. The present study reviews the current advances in EMFs applications in sewage and wastewater treatment and the mechanisms of action. In addition, future perspectives of technologies in this field are reviewed.

Key words: Electromagnetic Fields, Wastewater Treatment, Sewage, Magnetic Treatment, Mechanism of Action, Magnetized Water.

Dramatic increase in the world population, transition to the modern life and increasing the polluting agents have introduced the water pollution as the main problem of human colonies, especially in municipal areas. Various methods have been developed for the wastewater treatment (WWT). Sewage treatment is the process of eliminating contaminants from wastewater, including household sewage and runoff[1]. In this process, for physical, chemical and biological contaminants appropriate physical, chemical, and biological processes are used, respectively. Conventional WWTs consist of three stages: primary, secondary and tertiary treatment. In a brief, the whole process is as follows: In primary treatment the sewage is temporarily hold in a quiescent basin to settle heavy solids while oil, grease and lighter solids remain in the surface[1, 2]. After removing the settled and floating materials, the remaining liquid is discharged or subjected to secondary treatment where dissolved and suspended biological matters are removed[2]. In this step, indigenous and water-borne microorganisms are used in a controlled environment to treat water and remove organic and phosphorus compounds. After the separation of microorganisms, the treated water goes to the tertiary treatment that includes different processes to guarantee the release of the treated water into a highly sensitive or fragile

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ecosystem. The conventional WWT methods have various drawbacks including high cost, environmental adverse effects and low outcome. During the recent decades, electromagnetic fields (EMFs) have shown great potentials in medical, industrial and environmental applications. Various therapeutic and diagnostic modalities of EMFs have been introduced for various disorders including musculoskeletal diseases[3], cancer treatment[4], neurological disorders[4, 5], wounds[6-9]. In addition, EMFs have shown promising potentials in different environmental and industrial issues such as pollution, food quality, irrigation, etc.

Sewage and WWT using EMFs is one of the promising research topics with significant progression during the last two decades[10-17]. In this regard, studies have demonstrated promising potentials of EMFs for enhancing water and wastewater quality[11-14, 16-18].

Electromagnetic Fields in Wastewater Treatment

Findings of the previous studies have demonstrated the high efficacy of EMFs as adjunctive or alternative of conventional WWT. Different modalities of EMFs can improve different steps of WWT process. For example, EMFs can improve the activating sludge and disinfection processes. In addition, antimicrobial and antibacterial properties of different frequency-bands of EMF spectrum like ultraviolet (UV) radiation are useful in the WWT [11, 13, 14, 16, 17, 19, 20]. These antimicrobial effects can be used in the disinfection process of the WWT process or as a stand-alone process of wastewater treatment. Furthermore, EMFs can alter physical and chemical properties of water molecules, microorganisms and organic compounds that will be used to facilitate sewage treatment process[11, 13, 14]. Magnetic fields (MF) can modify the activity of activated sludge that is a crucial factor in the WWT process.

The main research fields of EMF applications in WWT are magnetite slurry, magnetic particles, altering activated sludge, and magnetic powder. Majority of magnetic WWT systems are similar in using magnets or electromagnets as the core element of a complete system to eliminate pollutants from wastewater including phosphate, heavy metals organic ions.

Most of previous studies on the applications of EMFs in WWT have focused only on the usage of magnetite (magnetic particle and slurry). There are few published studies on the specific consumption of MF effect on the sewage properties. One of the main processes of using EMFs in WWT is magnetically seeded filtration that has various applications in industrial WWT. In this process, particles with higher magnetic susceptibility are used to flocculate with weak magnetic and nonmagnetic particles present in the suspension which in turn form paramagnetic flakes that can be removed by a magnetic filter[21]. This process has been extensively used in various industrial WWT processes including filtration of nuclear reactor coolant[22], removal of phosphate from water[23], recovery of ultrafine magnetic minerals like hematite and chromites[24] and separation of dissolved heavy metals from wastewater[25].

There are a plenty of well known methods applied on a large-scale for phosphorus limitation in wastewater. Most of phosphorus limiting methods in wastewater treatment use appropriate bacterial strains which their growth and biomass increase facilitates accumulation of phosphorus compounds P-PO4 and to limit phosphorus concentration in wastewater[20, 26-28]. The other common and effective method which is currently used for phosphorus removal in WWT process is introducing chemical reagents to the systems. These reactive chemical agents initiate the phosphate ion precipitation from the wastewater solutions in forms of slowly soluble salts or make adsorption components after combining with phosphate ion. The most commonly used compounds are aluminum (Al), iron (Fe) and calcium (Ca) salts[29]. Activated sludge methods are quite complicated and suitable for microorganisms aerobic/anoxic conditions need to be prepared. In addition, the bacteria of activated sludge are sensitive to the concentration of the influents, wastewater pollutants concentration and toxic substances[27, 28]. However, the chemical reagents have several disadvantages including difficulties in practical settings, high costs and increasing the sludge mass[27, 28]. Although chemical precipitation process has high efficiency for WWT, is quite expensive and increase the sludge mass[19]. Therefore, developing new effective systems with high performance in phosphorus and organic compounds removal from the wastewater is of prime importance. To bridge the gap, various scientific attempts have been initiated to develop independent systems that produce high quality effluents and also adjunctive of alternative technologies that can improve the efficiency of the current WWT plants[30-32]. The impact of the ultrasounds, microwaves, electrical current, and UV or gamma radiation were tested. Previous studies have shown that an appropriate EMF can intensify coagulation and the biodegradation of organic compounds of the activated sludge and under specific conditions can be one of the elements determining the effectiveness of pollutant removal[32, 33]. Krzemieniewski *et al*. (2004) investigated the possibility of an EMF influencing the intensification of phosphorus and organic compound (COD) removal from domestic wastes[14]. Influence of the intensity of EMFs was assessed on phosphorus and COD removal from domestic wastewater in steel packing systems.

Magnetic Water Treatment

Water is a paramagnetic compound with a small and positive susceptibility to MFs. The water molecules like other paramagnetic compounds are slightly attracted by a MF and the material does not retain the magnetic properties when the external field is removed[34, 35]. When passing a MF, water gains a magnetic moment that persists for 24 to 48 hrs. The outcome of magnetic water treatment (MWT) depends on magnetic field intensity, composition of dissolved salts and velocity of crossing a magnetron of 0.5 inch diameter. MWT is a non-chemical treatment of water that does not require any filtration substitutes. Various mechanisms of action have been proposed for physiochemical processes of MWT. Majority of these explanations have focused on the formation of scale and methods for its prevention[36]. Magnetic treated water undergoes several changes in its physical properties. It also exerts several effects on the soil water plant system. Total salt removal from the soil after the course of leaching of soil irrigated with magnetized water. Leaching the soil with magnetized water significantly increased available soil phosphorus content compared with the leaching with normal water at all soil depths. Behavior of nutrients in a MF is a function of their magnetic susceptibility.

MWT is a simple and efficient approach where the water flows under a MF or combination of MFs which consequently alters some of its physicochemical properties (Fig. 1). Wahid *et al*. (2001) proposed a magnetic treatment system to investigate to the feasibility of magnetic technology in assisting sedimentation of suspended particles and to understand the mechanism and impact of magnetic treatment in the sewage[37]. They designed a series of electromagnets magnets as a magnetic reactor in a treatment process for the sewage where the sewage was flown through the reactor under a relatively strong magnetic field (Figs. 2&3). Their experiments indicated that suspended solids removal increases as magnetic field strength and exposure time increased and flow rate decreased[37]. They showed that MF increases the suspended solids removal by 41 percent to 49 percent at 670 Gauss compared to untreated raw sewage[37]. Furthermore, they showed that MF enhances the suspended solids removal through decreasing the settlement time of sludge as well as increasing the sludge density. Magnetic treatment is significantly advantageous in reducing the sedimentation tank volume as well as increasing the treatment plant efficiency[37].

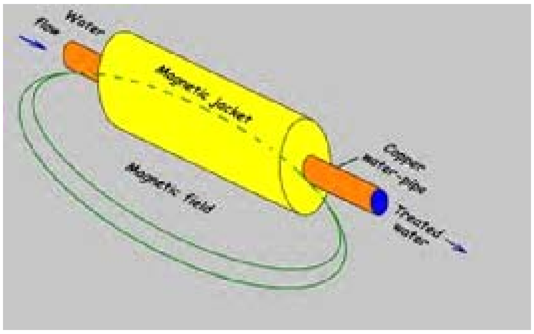

Fig. 1. Schematic diagram of magnetic water system

MWT has several applications in medical, industrial and environmental fields. Some of these applications are medical heal effects of magnetized water, preventing scale deposition, improving irrigation water quality and crop yield, scale elimination, corrosion control and wastewater treatment.

Magnetic Wastewater Treatment

The effectiveness of MWT in wastewater treatment, scale elimination and prevention and increasing biodegradability of microorganisms is strongly affected by the chemical properties of the treated medium, strength and configuration of the MF, thermodynamic properties of the water and fluid flow characteristics. In MWT, to achieve desired outcomes, the four important conditions should be observed: a) The water path must be perpendicular to the magnetic lines of force; b) Water should first cross the south magnetic lines and then continue to break wider and denser alternating reversing polarity lines, until leaving the magnetic chamber through the single North Pole flux path; c) The capacity of a magnetic conditioner can be determined by the gauss strength, flux density, area surface of the exposure of the number of fields and the distance between alternating poles; d) Water should be under pressure and flowing with as minimum turbulence as possible, just before entering and during its travel through the MFs.

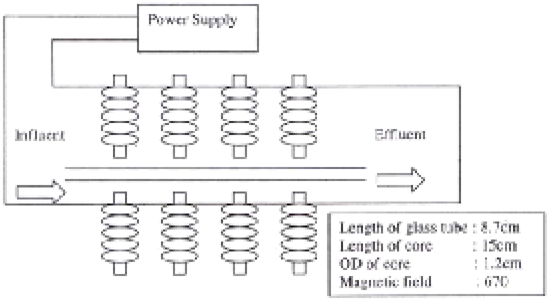

Fig. 2. Schematic Diagram of general magnetic reactor (electromagnets) for sewage treatment[37]

Magnetic Treatment and Activated Sludge

Biological processes are used to convert organic materials existed in wastewater into flocculant and settleable biological and inorganic solids. Under these processes, biodegradation, the biodegradability of sludge is increased. Activated sludge process and its modified forms are among the most commonly used biological processes[38]. There have been numerous studies on the effect of MF on living organisms, but the results are usually conflicting. Although some of them show a negative effect[39], most of them show an enhancement in growth[40, 41]. The magnetic induced effects on the living organisms depend on the strength of MF and the exposed microorganism type. Although the exact mechanisms of action of these effects have not been understood in detail, it is obvious that MF has not a lethal effect on microorganism. MF exposure can increase or decrease the growth rate of a living organism depending on the physical parameters of the field like type of magnetic pole, South pole or North Pole, exposure duration, intensity,etc[42]. Goodman *et al.* evaluated the effects of weak pulsed magnetic fields (1.5 mT peak ,2s on 2s off) on Escherichia coli strains[43]. Their results showed that the synthesis of numerous proteins are either increased or decreased by a factor of 2 or more[43]. Tabrah *et al.*[44] indicated that 48-h exposure to a 60 Hz sinusoidal electromagnetic field (intensity of 0.2 mT) significantly increased the number of azide-induced TA 100 revertant colonies of Salmonella typhimurium.

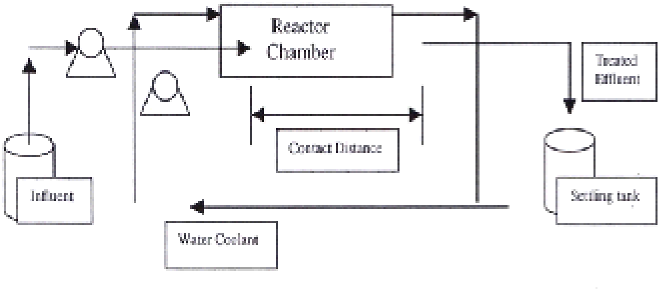

Fig. 3. Schematic diagram of a common magnetic wastewater treatment[37]

So far, few studies have been conducted on the application of MFs in the WWT, and in most of them, MF is used only for separation of solids or attached microorganisms from effluent[12]. However, previous studies have had an important outcome: MF exposure can increase the biological activity. MF, because of it intrinsic characteristics, can increase the bacterial activity, and the effect was far more noticeable in heterogeneous cultures (sewage) than in pure culture. Another important outcome with respect to MFs is their ability to detoxify toxic compounds. Jung *et al*. [45] performed a study to show the effect of MFs on the rate of phenol biodegradation by using immobilized activated sludge. A 30% increase in biodegradation rate was obtained by applying a magnetic south pole of strength of 0.45 T to the bioreactor with microorganisms immobilized on the beads as compared to the control. Magnetic north pole irradiation inhibited this type of bio-oxidation.

Optimum pH for the activated sludge was reported 7.5 both with and without MF application. The studies showed that although MFs do not exert a lethal effect on the activated sludge efficiency, they have a positive effect on substrate removal rate which is directly related with the magnetic strengths with maximum at 17.8 mT. Although low strengths of MF, about 9 mT, exert almost no effect, higher strengths of MF, about 54 mT have negative effects on substrate removal and microorganism growth rate[45].

Biological Treatment of Wastewater by Magnetic Field

MF has intrinsic antimicrobial properties which have raised the research attention to disclose the theory and improve practical modalities based on MFs for wastewater treatment[46-48].

MF can influence the growth of microbe. MFs can intensify the stationary-phase-specific transcription activity of the bacteria, *Escherichia coli*[49]. Nakamura *et al*. (1997) evaluated the aerobic growth of bacteria Bacillus subtilis and found that the cell number in an inhomogeneous (5.2–6.1 T) MF was about twice higher compared with the reference (7 T) in the stationary phase[50]. Furthermore, MF could affect biodegradation ability of microbe. Tomska and Wolny (2008) demonstrated that exposing activated sludge system by MFs improved the nitrogen compounds transformations in the system compared with the system without MF. Furthermore, oxygen uptake rate of second nitrification phase increased as high as twice[51].

In line with the researches assessing the effects of different MFs on the performance of activated sludge, the performance of direct current MF in degradation of different substrates like glucose by the activated sludge[10]. They showed that increasing the MF strength increases the substrate removal rate that reached to a maximum level (at magnetic strength of 17.8 mT), whereas further increase in MF decreased the removal rate[10]. Aarthi *et al*. (2004) demonstrated that pretreatment of Flavobacterium species with sinusoidal magnetic field increased the degradation efficacy of the paper mill effluents[52]. Studies conducted on the effects of MFs on the capacity of bacteria for biodegradation of organic compounds in the sewages showed that biodegradation time, magnetic field induction, operating temperature and medium pH are the important factors[16, 53].

Pulsed Electric Fields in Wastewater Treatment

During the last three decades, various researches have been conducted on pulsed electric field (PEF) technology as an alternative to the traditional methods of WWT and thermal pasteurization of liquid foods. Many studies have demonstrated the feasibility of PEF technology to treat wastewater and to produce safe, fresher and more nutritious foods covering a wide range of liquids such as milk and dairy products, liquid whole egg and derivatives, fruit juices and fruit juice-based beverages and vegetable soups among others[54-60]. Different prototype and small-scale PEF units have been developed with new designs in the treatment chamber geometry, such as the co-field design (applying the electric field in the same direction as the fluid flow)[61] to generate an uniform electric field to yield higher performance for experimental and pilot studies (400–2000 L/h)[62, 63]. All these efforts resulted in the manufacturing of commercial-scale PEF units for food processing with an overall flow rate of 400–6000 L/h[64]. The PEF technique has been used in various industrial wastewater treatment systems for a decade. In addition, utilizations of the PEF technique in the juice processing industry is currently feasible and in commercial use in some countries like the USA[65]. However, majority of the manufacturers subsequently switched from PEF to high-pressure processing for undisclosed reasons. Despite the large quantity of scientific data available in the literature about the benefits of PEF processing and the technology transfer projects, there is still very little industrial implementation of PEF for pasteurization of liquids and it is limited to waste water treatment[64]. The main reason for the limited application of PEF technology may be the lack of systematic cost analysis studies of the commercial application of PEF processing. It has been stated that the low implementation of PEF in industry is mainly because of the high initial investment costs and elevated processing costs[66]. However, only a few studies have been conducted on cost analysis of PEF food processing[67].

PEF is a new technique proposed for treatment of combined sewer overflows (CSOs)[64]. In the PEF process, a liquid which can be wastewater or nutritious liquid foods is passed through a small treatment chamber, where it is subjected to short (1–10 µs) pulses of very high voltage, typically 20–500 kV. The high voltage field created across the liquid (1–35 kV/cm) kills microorganisms by disrupting their cell membranes via an effect called "electroporation," the dilation of the pores in the cell wall. If the intensity of electric field is high enough with long enough duration (µs), the pores are irreversibly damaged, and the cell dies.

To achieve the effectiveness of conventional pasteurization with kill ratios of 5–9 log, multiple treatment chambers in series can be used to apply the PEF pulses to a stream. Log reduction is defined as the ratio of bacteria at the outflow to the inflow of a treatment process. A 5-log reduction (typical for food pasteurization) means that 1 bacterium in a sample remains alive for every 100,000 present prior to treatment. Because it uses an electric field, PEF has no chemical impact on the liquid under treatment. The energy range in PEF technology is sufficient to disrupt living cells, but not powerful enough to create chemical reactions.

The main issue in the development of PEF technology is applicability and cost-effectiveness of a PEF system to bacterial reduction on stormwater in CSOs, and its broader applicability to sewage treatment, sludge minimization, and other WWT applications.

Technological Considerations in Magnetic Wastewater Treatment

One of the common magnetic WWT method is magnetic particle technology which is based on absorption and coagulation process[17]. This technique can be used for various wastewater applications such as metal recovery from electroplating rinse water, sewage sludge and hydrometallurgical effluents. This process is based on attachment of wastewater pollutants to a magnetic carrier material (magnetite). After separation, the magnetic is recovered and reused in the process. Sakai (1994) studied the efficiency of such a system submerged filter system consisting of magnetically anisotropic tubular support media for sewage treatment with biofilm system. Activated sludge was supplemented with ferromagnetic powder for the preparation of the biolfilm. The biofilm was formed within 15 mins on magnetic support media by magnetic attraction. This magnetic based WWT system was able to treat sewage containing 0.2 g/l COD removing 72-94% COD with a retention time of 8h. During recent years, a considerable research attention has been focused on development of waste water treatment by static magnetic field. The scarce information is available on the effect of MF on biodegradation process of wastewater organic substrates, especially transformations of nitrogen compounds. The appropriate strength of MF to improve biological process of WWT has not been defined. The MF induction reported by previous studies is wide and ranges 7 to 490 mT[10, 33, 45, 68, 69]. Jung and Sofer[68] showed that application of MF at induction of 150 and 350 mT improved of phenol biodegradation through immobilized activated sludge. They used unipolar South Pole of MF. However, in the earlier studies Jung *et al.*[45] showed the positive effect of MF on phenol biodegradation but at induction of 490 mT. Yavuz and Çelebi[10] demonstrated that MF of 17.8 mT induction generated by direct current supplied solenoid supported glucose biodegradation with activated sludge action. Cebkowska[33] showed that static MF at induction in the range from 5 to 140 mT generated by electromagnet coils intensified of biodegradation process by activated sludge for majority of testing organic substrates. The main issue in the development of commercial systems of wastewater treatment based on EMFs is conducting cost analysis of experimental systems and designing cost-effective and practical systems with reasonable cost.

CONCLUSION

EMFs have shown promising potentials in wastewater treatment. MFs have intrinsic characteristics like antimicrobial and antibacterial properties which are beneficial in wastewater treatment. In addition, the interactions of EMFs with living organisms as well as different compounds of wastewater can be used as adjunctive process or facilitating the conventional steps of wastewater treatment. Magnetic treatment can increase the biodegradability of organic compounds existed in the wastewater. In addition, MFs improve the activated sludge process and removal of suspended solids from the sewage. The main mechanisms of action in improving the suspended solids removal field are accelerating the settling of sludge and increasing the sludge density and sedimentation rate. EMF based technologies have several advantages over conventional wastewater treatment including safety, compatibility and simplicity, environmentally friendliness and low operating cost. We can expect further development in the EMF based technologies in wastewater treatment.

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