Chapter

Removal of *Escherichia Coli* Using Low-Frequency Electromagnetic Field in Riverbank Filtration

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Abstract

An increase of pathogenic bacteria (*E. coli*) in river water is a concern as it is the main precursor to health hazard disinfection in conventional drinking water treatment systems. Riverbank filtration (RBF) is a non-chemical techniques and natural treatments that efficient in reducing or removing the contaminants in the water. Therefore, this study aimed to remove *Escherichia coli* (*E. coli*), and reduce the concentration with low-frequency electromagnetic fields (LF-EMF) as a component of the non-ionising radiations in RBF. This research design and construct a LF-EMF device on horizontal coiled columns that were capable of producing uniform magnetic fields in the frequency range of 50 Hz. A magnetic field density was varied at 2, 4, 6, 8, and 10 mT. The diameter of column was 50 mm, which underwent 6 hours of LF-EMF exposure at 50 mL/min of water flowrates. The maximum removal efficiency of *E. coli* in was 100% at 6, 8, and 10 mT of magnetic field exposure. These results indicated that the *E. coli* in the sample of water that was exposed to the LF-EMF was statistically significantly decreased. The magnetic intensity of the LF-EMF changed the characteristic responses for *E. coli* bacteria.

Keywords: electromagnetic field, low-frequency, *E. coli*., growth, river water

1. Introduction

Water is a fundamental need, and the most abundant of resources [1]. However, the World Health Organisation (WHO) stated that, in 2012, about 780 million people were without an adequate drinking water source [2]. Hence, the demand for good quality and clean drinking water has increased, especially among Malaysian consumers. Raw water originating from surface water and groundwater needs to be treated before the water is made potable. According to statistics in 2017, in Malaysia, 500 water treatment plants (WTP) were in operation to treat raw water, and produced about 16,536 million litres per day (MLD) of drinking water to consumers.

Clean and safe water is one of the most pressing global health-affecting and environmental issues. Generally, in Malaysia, surface water is exposed to organic, inorganic, and microbial pathogen contamination due to poor management of septic tanks, wastewater, and agricultural runoff and earthwork products [3]. Approximately 99% of water supply for domestic uses in Malaysia originate from surface water such as rivers and streams, while another 1% originate from groundwater [4]. The surface water in the country has also been polluted with, for example, biological contaminants such as viruses, bacteria, and protozoa which are capable of causing illnesses in humans like bloody diarrhoea, affecting human health as well as the environment [5].

According to the Department of Environment (DOE) Malaysia's annual report, 48% of the 473 rivers monitored in 2014 have been contaminated by these sources. This high percentage reflects that the water resources in Malaysia are contaminated, and the condition may continue to worsen. Among all the pollutant loads entering surface water, bio-colloids are the major pollutants attributed by wastewater discharge and surface runoff. These bio-colloids usually refer to microorganisms in the water, such as bacteria and protozoa [6]. About 842,000 death cases involving diarrhoeal illnesses because of drinking water contamination were reported [7]. The situation can worsen during extreme weathers such as El Nino (drought), and El Nina (floods) that have a great impact on the quality and quantity of the water resource [8]. According to previous studies, contamination of bacteria significantly increases in surface water during these events [9]. This poses more challenges to the authorities in delivering and providing safe drinking water via the conventional treatment system because of the low surface water level, and high pollutant loads [10]. Therefore, to ensure a stable and safe drinking water supply, alternative methods for water management are necessary especially during extreme weather conditions.

Riverbank filtering (RBF) is an attractive option that can be applied for effective water treatment. RBF is a technique that covers both shallow groundwater and river water that have crossed through the banks of rivers, or riverbanks to well extractions [11]. Most of the suspended and dissolved contaminants, including viruses and pathogenic bacteria, are filtered out as surface water is filtered through aquifer materials, and the sediments of the riverbed [12]. Abstracting of riverbank water can overcome water shortage due to extreme events such as floods and droughts that cause water levels to increase on the ground, or reduce underwater intake pipes, causing disruptions in water transfer to treatment plants [13]. Although RBF is a capable method for improving surface water quality, it does not abolish the problem. Abstracted well water quality is highly dependent on several factors, such as groundwater and river water quality, temperature and pH of water, water residence time, medium porosity, and oxygen concentrations [14]. According to Levantesi et al. study, the breakthrough of bacteria and turbidity occurred in a shallow drilled well (3–6 m) due to the short travel time, especially during monsoon seasons [15]. This condition urges for appropriate treatment applications to further enhance the ability of RBF in bacteria and inorganic substance removal.

Indicator bacteria, including the total coliforms, *Escherichia coli* (*E. coli*), *Enterococci*, and *Clostridium perfringens*, are commonly used to measure drinking and raw water quality. The presence of faecal coliform and *E. coli* is likewise a potable water contamination indicator through animal or human faecal matter [16]. *E. coli* bacteria indicate the potential presence of pathogenic microorganisms in natural and treated waters. *E. coli* can cause a variety of intestinal and extra-intestinal infections, such as diarrhoea, urinary tract infection, meningitis, peritonitis, septicemia, and gram-negative bacterial pneumonia [17]. To date, many treatment methods for the removal of *E. coli* have been introduced in treatment plants, such as membrane filtration [18], soil aquifer treatment [15], slow sand filtration [19], granular activated carbon (GAC) adsorption [20], and advanced oxidation [21]. All these methods have long been used in water treatment, and proved effective for bacteria removal. However, there is no information about non-ionising radiation applications in water treatment plants in Malaysia. This method is a better option for new applications in RBF systems based on the requirements of packing materials around the well screen.

Despite the numerous advantages of RBF, it also has several limitations [22]. Seasonal variations have an impact on the concentrations of *E. coli* in riverbeds, where they increased during the wet seasons [3]. Therefore, researchers have been conducting studies to explore and develop an efficient but cost-effective method capable of removing the *E. coli* using new application techniques. Low-frequency electromagnetic fields (LF-EMF) are a component of the non-ionising radiations used to treat and control the effective growth of *E. coli* bacteria [23]. Application of the LF-EMF on the *E. coli* bacteria has shown that exposure to non-ionising, electromagnetic radiation can induce numerous and quite varied removal effects [24]. Due to the capability of LF-EMF to remove the *E. coli* bacteria, this application was introduced as an alternative technique of *E. coli* removal in RBF. Therefore, evaluating the proposed LF-EMF effects on the RBF system is important to determine its effectiveness for the removal of *E. coli* in drinking water supply.

1.1 Malaysia's drinking water resources

Malaysia has had abundant and rich water resources throughout the years. The main source of drinking water in Malaysia is groundwater and surface water. Approximately 99% of water for domestic uses in Malaysia are from surface water, while another 1% of the supply is from groundwater [25]. Malaysia's internal water sources are estimated to be about 580 km^3/year, with 30% of water production for municipal uses [26]. Water supply from surface water is widely used as drinking water, such as water withdrawn from Sungai Kinta, Sungai Langat, and Sungai Selangor [27]. Water supply from groundwater intake from a few states in Malaysia such as Terengganu, Kelantan, Perlis, Kedah, Pahang, Sabah, and Sarawak are also used for drinking water [28]. According to the data published by Suruhanjaya Perkhidmatan Air Negara (SPAN) in 2015, only 1.5% of total groundwater supply is present in Malaysia, and there was an increase in groundwater usage by 3.3% from the year 2014 to 2015 (SPAN, 2015). Nonetheless, the key issue to be considered is the quality of the water sources for drinking water supply. Both surface and groundwater sources are easily affected by the surrounding changes, whether manmade or natural. Therefore, it is important to determine undesired constituents, and monitor the characteristics of the water sources to ensure the pollutants in the water do not exceed the standard limits for water supply stated by the National Water Quality Standards for Malaysia (NWQS), and the Ministry of Health (MOH).

1.1.1 Quality of water

The Department of Environment (DOE) uses the National Water Quality Standards for Malaysia (NWQS) and Water Quality Index (WQI) to evaluate the status of the water source quality [26]. The WQI, introduced by the DOE, has been practiced in Malaysia for about 25 years, and serves as the basis for the assessment of environment water quality, while the NWQS classifies the beneficial uses of the watercourse based on WQI [29]. To design the drinking water quality management system, the assessment of water quality is an important step in determining the possible problems in the quality of the drinking water source. Basically, the characteristics of water quality are determined by physical, chemical, and biological factors to describe the overall condition of the water quality and its suitability for a specific use.

1.1.2 Microorganism pollution

The occurrences of pollution and indicator pathogenic bacteria in potable water depend on a number of factors, including the intrinsic and chemical characteristics of the catchment area, and the range of human activities and animal sources that release pathogenic bacteria to the environment. Sources of pathogenic bacteria in potable water are numerous and, for operational efficiency, are typically assessed by faecal indicator bacteria investigation. In terms of biological characteristics for safe drinking water supply and drinking water distribution systems, water is one of the transmission routes for pathogenic microorganisms [2]. In spite of having enhanced water management and sanitation, waterborne-diseases and outbreaks may continue to occur [30]. Drinking water polluted by microorganisms of faecal origin is a current worldwide health concern because of epidemic occurrences globally in relation to microbial-contaminated water. In drinking water, these microorganisms of interest include protozoa, bacteria, viruses, algae, and helminths. An overview of these microorganisms is given in **Table 1**.

Faecal coliforms are bacteria which fulfil all the criteria used to define total coliforms, with the additional requirement that they grow and ferment lactose with the production of acid at a scientifically accurate 44.5°C [31]. This bacteria of the coliform subgroup has been found to have a positive correlation with faecal contamination of warm-blooded animals [32]. However, several thermotolerant coliform bacteria, by definition by the genus *Klebsiella* bacteria, have been isolated from environmental samples with the apparent absence of faecal pollution [33]. Similarly, Revetta et al. reported that other members of the thermotolerant coliform

Types	Description	Remarks
Bacteria *Vibrio Cholerae* *Escherichia coli* Legionella *Shigella* spp. *Samonella* spp.	• Single cell organism with size ranging from 0.1 to 10 μm. • Negatively charge surface • Aerobic, anaerobic, facultative • Motile and non-motile	• The most reported water-borne plaque are involve of bacteria
Protozoa *Cryptosporidium parvum Giardia lamblia* Entamoeba dispar *Entamoeba histolytica*	• Group of unicellular and non-photosynthetic organism with diameter size between 1 and 102 μm. • Negatively charge surface aerobic and anaerobic motile and non-motile	• Under water-borne disease standpoints, the four listed Protozoa are consider as the greatest risk in water supply
Virus T-4 coliphage Adenovirus Enterovirus Rotavirus MS-2 coliphage	• Smallest of waterborne agents with diameter size of 0.02–0.2 μm Negatively charge surface	• Poliovirus and Hepatitis A are the only known virus that have been documented to be associated with water-borne transmission
Algae Volvox Euglena Cyclotella Synedra Chlorella Anabaena	• Diameter size: 1–102 μm Negatively charge surface aerobic motile and non-motile	• Algae are common living organism in water supply and play important part in nutrient cycle. But a few algae are pathogenic to human because it produce endotoxins that can cause gastroenteritis
Helminths	• Diameter size: 1–102 μm Negatively charge surface aerobic motile	• Effective treatment and disposal of sewage water can control the parasitic worm in water supply

Table 1.
Microorganism in drinking water sources.

group and *E. coli* have been detected in clean areas, and were associated with regrowth events in the water distribution systems [34]. Faecal coliforms demonstrate a survival of the bacteria form similar to pathogenic bacteria, and also have usefulness as indicators of bacteria, tended to be replaced by *E. coli*.

Recently, the faecal coliform group has been extended to include other characteristics, such as β-D-*galactosidase*-positive reactions [35]. *E. coli* is a specific indicator for the presence of the faecal coliform group, and is the most reliable indicator of enteric pathogens [36]. Several studies have indicated that *E. coli* is an indicator of choice to indicate the occurrence of recent faecal coliform in drinking water. Currently, *E. coli* appears to provide the best bacterial indication of faecal coliform, and only several strains of *E. coli* in drinking water can cause diseases [37]. In several countries, this organism has been included in their regulations as a primary indicator of faecal contamination in drinking water [38]. Therefore, *E. coli* is the best faecal indicator to inform public-health risks associated with the consumption of contaminated drinking water.

Escherichia coli or *E. coli* is also known as a facultative anaerobic bacterium that is gram-negative. Cells of *E. coli* are typically rod-shaped with a cell volume of 0.6–0.7 μm^3, 2 μm long, and 0.5 μm in diameter [39]. Generally, *E. coli* is found in the faeces of healthy cattle, and is transmitted in the lower intestinal tracts of warm-blooded organisms, including humans and animals [32]. In 1885, this microorganism was discovered by Theodor Escherich, and was first classified as a human pathogen in 1982. Most of the *E. coli* strains harmlessly colonise the gastrointestinal tracts of humans and animals as normal flora. However, other strains grow into pathogenic *E. coli* by acquiring virulence, which is caused by bacteriophages, plasmids, transposons, and pathogenicity islands. Differences in survivability, external structure, size, shape, and zeta potential are some of the factors that influence the behaviour of these bacteria. These pathogenic *E. coli* can be categorised based on pathogenicity mechanisms, serotypes, clinical symptoms, or virulence factors. Several of the enterohaemorrhagic *E. coli* are defined as pathogenic *bacteria* that produce Shiga toxins, and cause the life-threatening sequelae of haemolytic uraemic syndrome, and haemorrhagic colitis in humans.

1.2 Riverbank filtration (RBF)

Subsurface or groundwater in Malaysia are natural water sources that can be exploited to meet the demands for water of high quality. The RBF process is an existing method referring to the process of extracting potable water at the riverbank, utilising subsurface or groundwater to supply sources of high quality water [28]. RBF systems and natural treatment processes typically take place during water infiltration. **Figure 1** shows the natural process of extracting treated water from an adjacent pumping well to a river.

As illustrated in the figure above, the difference in hydraulic gradient causes the water from the river to flow towards the well during the pumping process. Additionally, the RBF process is known as a sustainable and economical method to improve poor surface water quality. A complex attenuation method occurs during the transportation of water through the aquifer layer, resulting in raw water of high quality. The high quality raw water is then supplied to the water treatment plants, making it easier to be treated at low operating costs by conventional treatment systems. Therefore, water from the well can be directly consumed with very minimum treatment in certain areas.

In many countries, river water has been treated to complement the existing water supply system through bank filtration, such as in Germany, Finland, France, Switzerland, Hungary, and the Netherlands. RBF has become an efficient, well

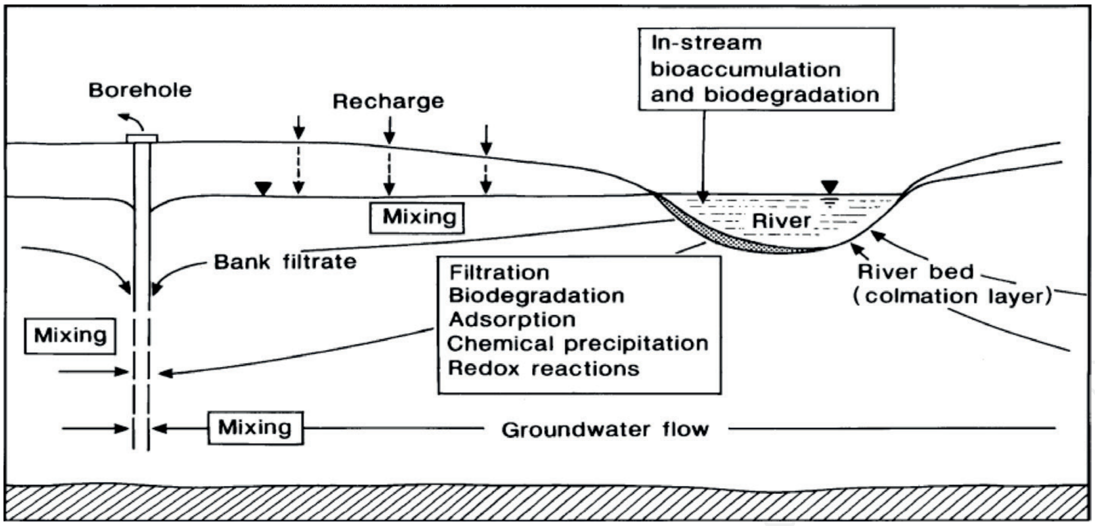

Figure 1.
Diagram of mechanisms in natural filtration by RBF system.

accepted technique for surface water treatment in many European countries. In Switzerland, 80% of the drinking water comes from RBF wells, with 50% in France, 48% in Finland, 40% in Hungary, 16% in Germany, and 7% in the Netherlands. Recently, other countries like Malaysia, India, as well as China and South Korea have started implementing RBF for drinking water supply [22].

Generally, RBF wells constructed in aquifers primarily consist of sand and gravel, with thin layer of granular aquifers (clay or silty sands). Removal of pollutants using RBF involves complex biological, hydrological, and geochemical activities through the aquifer layer during the filtration and infiltration of water. These processes consist of physical filtration, dilution, microbial degradation, precipitation, and sorption processes [1, 16]. According to recent studies in Europe and America, the RBF process is able to provide appropriate defence against microbial contaminants, and reduce the possibility of disinfection by-product formation. Additionally, RBF is also an effective method of removing common microbial pathogens such as *E. coli*, *Microcystins*, and *Cryptosporidium* during the infiltration process [22].

1.2.1 E. coli removal via riverbank filtration

RBF is a water treatment technology that involves extracting water from rivers by pumping wells located in the adjacent alluvial aquifer. In the underground passage, a series of physical, chemical, and biological processes take place, improving the quality of the surface water, while substituting or reducing conventional drinking water treatments. A study based on a model-oriented approach by Wang et al. used an example of riverbank wells near the Kuybyshev Reservoir, Russia [40]. The wells were designed in order to minimise the uncertainties in the estimated hydraulic parameters. During water transport towards the RBF wells, the water quality improved significantly, aided by processes like microbial degradation, ion exchange, precipitation, sorption, filtration, dispersion, and groundwater dilution.

Faecal and total coliforms are bacterial indicators that are widely used to monitor microbial water quality in developed and developing regions of the world. Faecal contamination of drinking water supplies is a public-health concern because they could contain pathogens that cause gastroenteritis, meningitis, and other waterborne diseases [37]. Potential sources of faecal contamination include direct discharge from human and animal wastes as well as non-point sources (agricultural and storm water runoffs). Majority of the RBF systems used in European countries and America alike have achieved excellent total coliform removal percentages, ranging from 99.2 to 99.99% (2.1–5 logs).

Removal of *E. coli* can stand between 99.9 and 99.994% (3–4.2 logs). It was also observed that 25–87% of groundwater can be co-extracted from these RBF wells [15]. According to the compiled literature above, the obtained results revealed the efficiency of the RBF system in eliminating bacteria mainly at the water-media interface. However, in a few situations, the problem of exceeding the stipulated bacterial limits persists. Therefore, it is advisable for the RBF system to be considered as a pre-treatment method to be combined with more effective conventional disinfection technologies in order to meet the target.

1.3 Principles of electromagnetic field treatment

Extremely low-frequency electromagnetic fields (ELF-EMFs) are ubiquitously present in various environments in everyday life. Generally the ELF-EMF spectrum is defined by frequencies from 3 to 3000 Hz [41]. These fields are generated via high-tension electrical distribution networks from residential and occupational sources by power lines and electrical devices. Normally, electric and magnetic fields occur together, and both fields weaken with increasing distance from the source. However, both these fields produce different effects on living organisms. In a large part of the world and Europe, 50 and 60 Hz (in the U.S.) sine wave signals resemble the household alternating current electrical power supply.

The principles and behavioural effects of electromagnetic fields (EMFs) have been reported since the 1970s. Recent studies in the field have shown that exposure to electromagnetic and non-ionising radiations can induce numerous biological effects [42]. For example, exposure to ELF-EMFs ranging from 0 to 100 Hz is capable of activating cellular immune responses. Various approaches have fixated on the probability of analogous effects regarding non-ionising radiation. Despite this, there have been an increasing number of studies suggesting that exposure to ELF-EMFs can affect and slow down the growth of *E. coli* bacteria. ELF-EMFs were also found to decrease the rate of growth in *E. coli* and *S. aureus*, inhibit the growth of cancer cells, and increase the rate of regeneration of worms.

1.3.1 Low-frequency electromagnetic fields

Low-frequency electromagnetic fields (LF-EMFs) are widely applied in electrical appliances and different equipment such as television sets, computers, and kitchen appliances. EMFs are classified into seven categories: (1) Extremely low frequency (0–300 Hz) used in biological processes, (2) low frequency (300 Hz–30 kHz), (3) middle frequency (30 kHz–30 MHz) used for amateur radio and remote controls, (4) ultrahigh (30–300 MHz) used in radio and TV, (5) super high (300 MHz–30 GHz) used in satellite communication, (6) extremely high frequency (30–300 GHz) used in radars, and (7) infrared (300 GHz–300 THz) and visible light (429–750 THz) used in light spectrums. The EMFs are characterised by a frequency of 50 or 60 Hz, and thus occupy the extremely low frequency (ELF), non-ionising range of the electromagnetic spectrum (3 Hz to 3 × 103 Hz) [43]. Although ELF-EMFs do not break molecular bonds or heat body tissue, they may interact with the human body through the weakly generated electric currents.

The LF-EMF is an effective technique in water treatment to prevent scale formation, and detach already-formed scale in industrial water systems. Many related studies have been conducted in the past 60 years, and several devices have been developed. Some researchers have found that EMFs can be implemented in soil and agriculture wastewater disinfection, in therapeutic practices, and in food protection technologies. It was also found that the EMFs have potential in controlling and removing bacterial growth on water treatment systems.

General operations of EMFs in water treatment systems involve the physics of interaction between a magnetic field and moving electric charges. The electromagnetic system consists of magnetic fields generated by coils wrapped around a pipe. The small electrical device treats the water with a patented technology by inducing variable electric currents at a continuous frequency to generate the magnetic field. The magnetic field removes the bacteria (*E. coli*) in the water, and reduces their growth. In other words, magnetic fields interact with the bacteria by the forces and electric field vectors generated. The EMF water treatment system for bacterial removal is presented in **Figure 2**.

1.3.2 Low-frequency electromagnetic fields for E. coli removal

Over the past few decades, it has been well established that non-thermal, non-ionising, extremely low frequency (<300 Hz) and low amplitude (0.2–20 mT) EMFs cause a number of different biological effects. The radiation is said to be capable of inducing physiological effects too [44]. Several studies have been performed to verify the direct effects exerted by EMFs on cellular functions. Bacteria were also tested in some studies using the ELF-EMF wave. The biological effects of EMFs are quite heterogeneous, depending on the types of cell studied, intensity, and types of field used. For more than three decades, various forms of electrical stimulation, including capacity coupling, direct current, and combined magnetic fields have been used as a therapeutic remedy. The current, and one of the most useful methods to investigate antibacterial effects due to magnetic fields is to use low-frequency EMFs, especially frequencies ranging from 50 to 60 Hz. On the contrary, even with some publications claiming the bio-effects of EMFs, there are plenty of studies showing no significant effects on living organisms. Podda et al. reported no change in oxidative DNA damage after 50 Hz EMF exposure was applied [45].

The implementation of magnetic fields in water treatment systems is a non-chemical method that covers a wide range of technologies. A recent study reported that EMFs had a positive effect on the efficiency in the number of bacteria removed in biological wastewater treatment [46]. EMFs also intensify the stationary-phase-specific transcription activity of the *E. coli* bacteria [47]. Additionally, Piydasa et al. observed growth responses of healthy *E. coli* cells exposed to EMF energy for 7 hours through the water treatment chamber [48]. They indicated a statistically

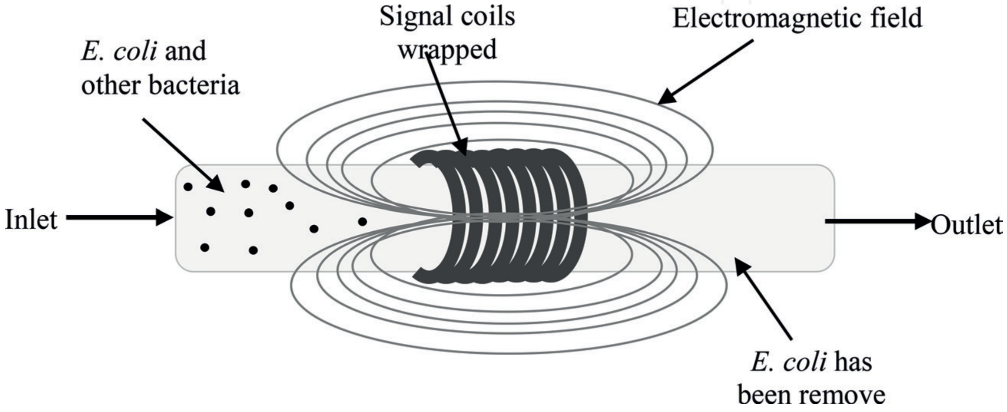

Figure 2.
Electromagnetic system for water treatment consists of magnetic field generated by coils wrapped around the pipe.

significant inhibition in the growth of *E. coli* that was attributed to the effect of different EMF waveforms and applied energies between two pulsed-electromagnetic field devices, Device D and Device G. Therefore, the stimulation or inhibition of the growth of *E. coli* and other bacteria depends on the frequency, field strength, and type of microorganism.

The data on LF-EMFs on *E. coli* effects for different environmental conditions, such as in water suspension, is important for future applications. As a major constituency, water is a medium for biological systems as well. The LF-EMF effects on H_2O molecules can be the mechanism in the creation of conditions for biological responses [49]. Different effects on the growth and viability of *E. coli* after bacterial suspension exposure to LF-EMFs have been reported at several frequencies that are resonant for H_2O molecules. According to Belyaev, LF-EMFs can cause direct physical damage, ionisation, or heating of *E. coli*, resulting in morphological changes after exposure [50].

1.3.3 Design and construction of LF-EMF exposure column pipe

The initial LF-EMF column structure was designed using the ANSYS Maxwell software program. A geometrical design of the model was created and drawn with the selected parameters. A fully-automatic meshing procedure was applied before the simulation was begun, after the structure had been modelled. In the ANSYS Maxwell 3D, the solutions were based on meshes by using thousands of LF-EMF coiled column elements. Accurate solutions based on coarse meshes using relatively few elements were obtained. To assist the meshing, the coil workpiece was created with multi-layers depending on the skin depth. The aim of this simulation was to generate a uniform magnetic field inside the column pipe, and assign the number of coil turns for the LF-EMF coiled column. **Figure 3** illustrates the cross-section structure of the LF-EMF coiled column, as well as the dimensions for one of the five column test models in this study.

There were five models of LF-EMF coiled columns built using ANSYS Maxwell software with different designs in this study. All the LF-EMF coiled columns were designed using gauge insulated copper wire with the conductivity of wound wires in a vacuum environment. The diameter range of the copper wires used was 1.5 mm. This range coil diameters were used to determine the most effective diameter of coil in generating a magnetic field at different column diameters (D_{column}), and number of coil turns (N). Theoretically, increasing the number of coil turns, with the same coil and the same current flowing, would increase the magnetic field strength. This relationship is defined as magnetomotive force (MMF), which refers to the flowing

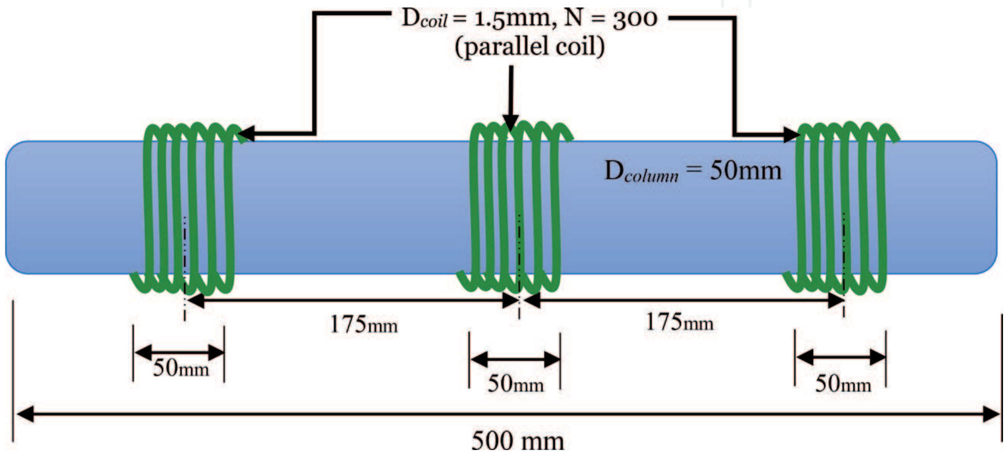

Figure 3.
LF-EMF column coil structure with workpiece dimensions.

of current through a coil of N turns. Therefore, an electromagnetic field strength can be determined by the *ampere-turns* of the coil; the more turns of wire in the coil, the greater the strength of the magnetic field.

The simulations of the coiled columns began with determining the N using 2 A excitation current to generate a magnetic field in the range of 2–10 mT. The magnetic field generated by the electromagnet was proportional to both N and *I* in the coil winding. Coil winding revolves around the geometry of the wound coil. In the opposite position of the wound coil is a calculated coil structure within the winding space. In this study, the N value and length of coil were designed depending on the length of solenoid, type of coil, and column diameter. The parameters of required number for coil turns (N), and diameter of coil were calculated using Maxwell-Ampere's law. The winding of the coil was manually wrapped parallel to the column at different diameters of coil and column. The coils were positioned in parallel to the column to generate a homogeneous horizontal LF-EMF coiled column with the water sample centred at the horizontal axis of the coil pairs.

The strength and intensity of the LF-EMF coiled columns depends on the N of coils, diameter of coils, and also the type of column material used as the core. In this study, five transparent polypropylene cylindrical columns with inner diameters of 50 mm, which were 500 mm in length were used. These cylindrical columns were of non-magnetic material that can be regarded as free space as they have a very low value of permeability. This material had no effect on concentrating the magnetic flux, and the magnetic field created by the current in the coils. The performance parameters of the coil used was dependent the geometry and coil dimension ratios. A smaller diameter of coil required much more number of coil turns, while bigger coil diameters used resulted in larger magnetic fields.

2. Material and methods

LF-EMF was produced with the coiled column and the sinusoidal 50 Hz magnetic field was generated by means of a solenoid, obtained with overlapped winding of copper wire with 500 mm of length and 50 mm diameter of column A and 80 mm diameter of column B. The power of 220 V was connected to solenoid coils waveform generator. The current flowing in the exposure devices was monitored by AC current in parallels of coils. In each coil, the number of turns was between 300 and 600 of 1.5 mm copper wire and the total resistance of the system was 1 Ω. The resulting of the whole inductance coil system was in the range of 2–10 mT. The density of magnetic flux was monitored using Tesla meter (BST600 Gauss meter/Tesla Meter) and field intensity was varied by ±0.05 mT.

According to previous studies, the method of IDEXX Colilert® 18 has been verified as an acceptable alternative to other test methods for the recovery of *E. coli* from source water, wastewater, and drinking water [51, 52]. The original method using mTEC agar is a standard method, and is recognised by the U.S.EPA as a useful method for monitoring recreational water quality [52, 53]. In this study, the Colilert® 18 method was compared to the original mTEC membrane filter method for enumeration of *E. coli* by parallel testing the water samples. The Colilert® 18 method was determined to be an acceptable alternative to the traditional mTEC standard method for monitoring *E. coli* levels in river water recreational areas based on the results of the study. No significant difference was found between the results of these two methods. Therefore, the Colilert® 18 method was suggested as an efficient and accurate means for testing water samples in this study.

2.1 Sample characterisation

The study site is located on Sungai Kerian at Lubok Buntar Kedah, Malaysia (**Figure 4**). The sample was collected during dry and wet seasons from Sungai Kerian and tube well. One hundred samples were collected; 50 sample for column test. Tube well water samples were collected in sterile amber glass bottles of 125 ml without headspace in order to prevent the formation of air bubbles and were airtight sealed. All laboratory analytical analysis was according to Standard Method [37]. Ten litres of river raw water sample was collected in polyethylene bottles. These samples were preserved in accordance with Water and Wastewater Standards and then stored at a temperature of less than 4°C. Laboratory apparatus used in this study were prewashed with 5% nitric acid (HNO_3) and rinsed with deionised water prior to testing.

2.2 Experimental setup

In this study, 13 runs of test with different magnetic field exposures were conducted. The horizontal transparent polypropylene cylindrical columns test with inner diameters of 50 mm were used. The coiled column test was built on the horizontal axis, and the magnetic field was generated by means of a solenoid, obtained with overlapping windings of copper wires, at 500 mm in length. The coils wrapped around the column transformed the magnetic fields controlled by the magnetic field power generating system. The maximum of effective current was 2 A at 50 Hz frequency. The magnetic generator consisted of a pair of solenoid coils, a current amplifier, and a waveform generator controller. The samples were exposed and placed in a horizontal column where uniformity of the magnetic field was optimal. Then, the LF-EMF coiled column experiment was started by pumping water samples in a horizontal direction into the column in order to ensure complete wetting of the particles [54]. A constant discharge rate was maintained using the peristaltic pump model Masterflex L/S HV 07522–20 at 50 and 100 mL/min to allow sufficient contact time between the magnetic field, and for the removal of *E. coli*.

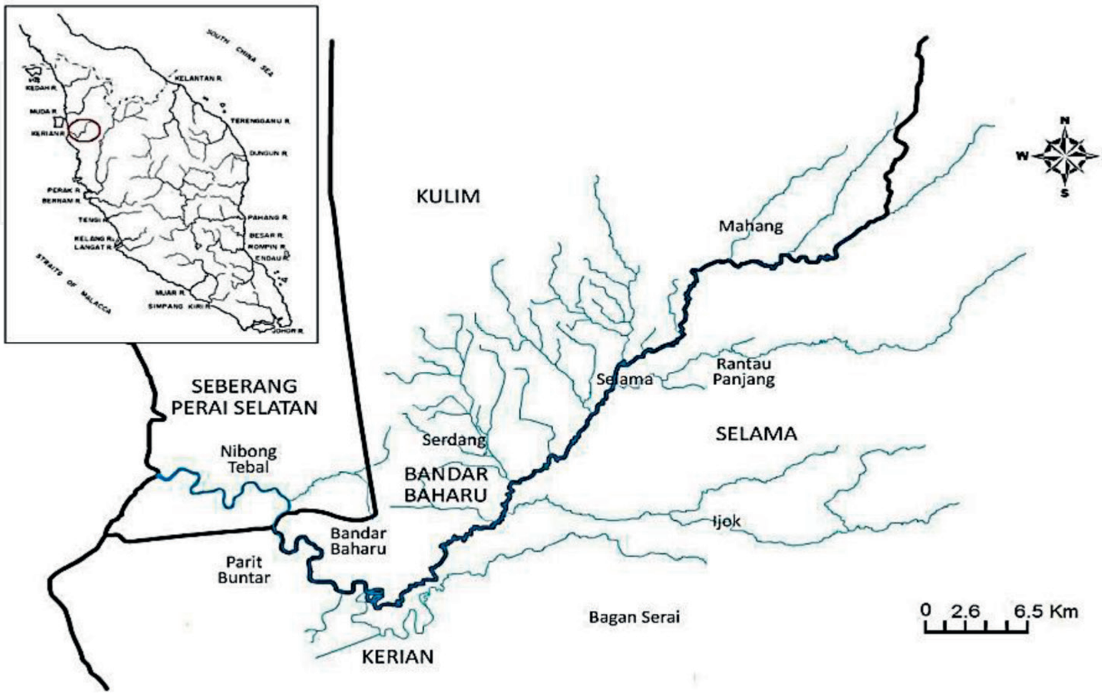

Figure 4.
The location of Kerian River in map of peninsular Malaysia.

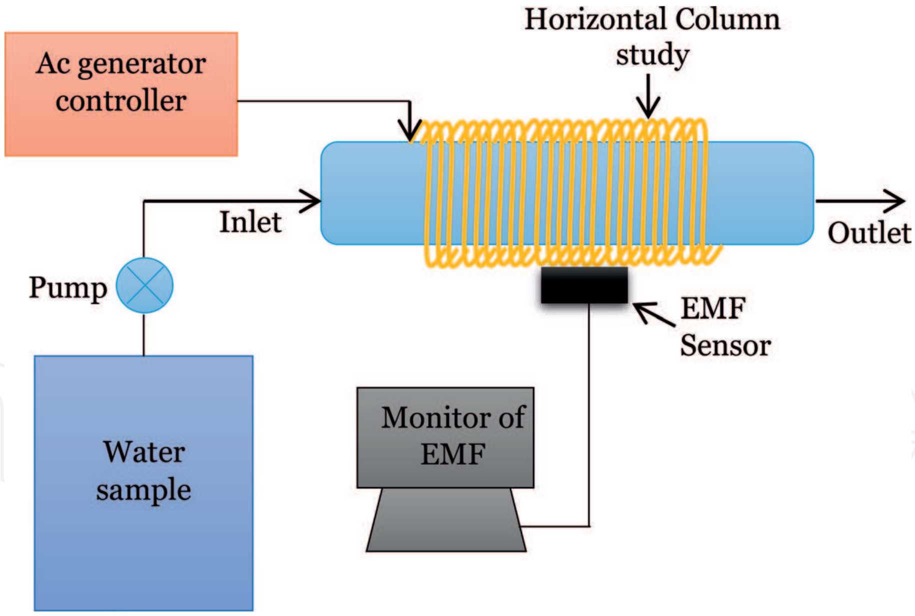

Figure 5.
Set-up for LF-EMF column study on E. coli removal by using magnetic fields exposure with alternating current.

The water sample was continuously fed into the column for a total experiment time of 6 hours. A total of 18 effluents were collected every hour directly into 100 mL sterilised vessels. The experimental setup is shown in **Figure 5**.

3. Result and discussion

Data collected from the experiments were analysed using Microsoft Excel and Origin-Pro 9.1 software. All the data and results are presented in the form of tables and figures. The findings include the simulation results and validation of the LF-EMF exposure, water sample characteristics, *E. coli* concentration in water quality, removal mechanisms, and potential of the LF-EMF column to remove *E. coli*. The results from the comparative analysis of *E. coli* removal before and after LF-EMF exposure with selected column diameters, and magnetic flux densities of 2 to 10 mT are presented in this chapter. In the present study, the optimisation of *E. coli* removal contact time for LF-EMF exposure was performed by using response surface methodology (RSM) to evaluate the optimal magnetic flux design, geometry, and parameters during the designing process.

3.1 Effects of magnetic field (β)

The column experiments consisted of LF-EMF coiled columns and river water, which was varied to analyse the effects of the magnetic field exposure on the removal of *E. coli*. Varying magnetic field intensities of 2, 4, 6, 8 and 10 mT reacted with the water samples at 50 and 100 mL/min flowrates. The data on the initial concentration of *E. coli* and the percentage of removal from the water samples were obtained.

Removal rates of *E. coli* in the water samples were measured at five different magnetic field intensities for column test. The diameter of column test was 50 mm, which underwent 6 hours of LF-EMF exposure at 50 mL/min (Q1), and 100 mL/min (Q2) water flowrates. **Figure 6** illustrates the percentage of *E. coli* removal after LF-EMF exposure. The maximum removal efficiency of *E. coli* in column test was 100% at 6, 8, and 10 mT of magnetic field exposure for Q_1. However, percentage of

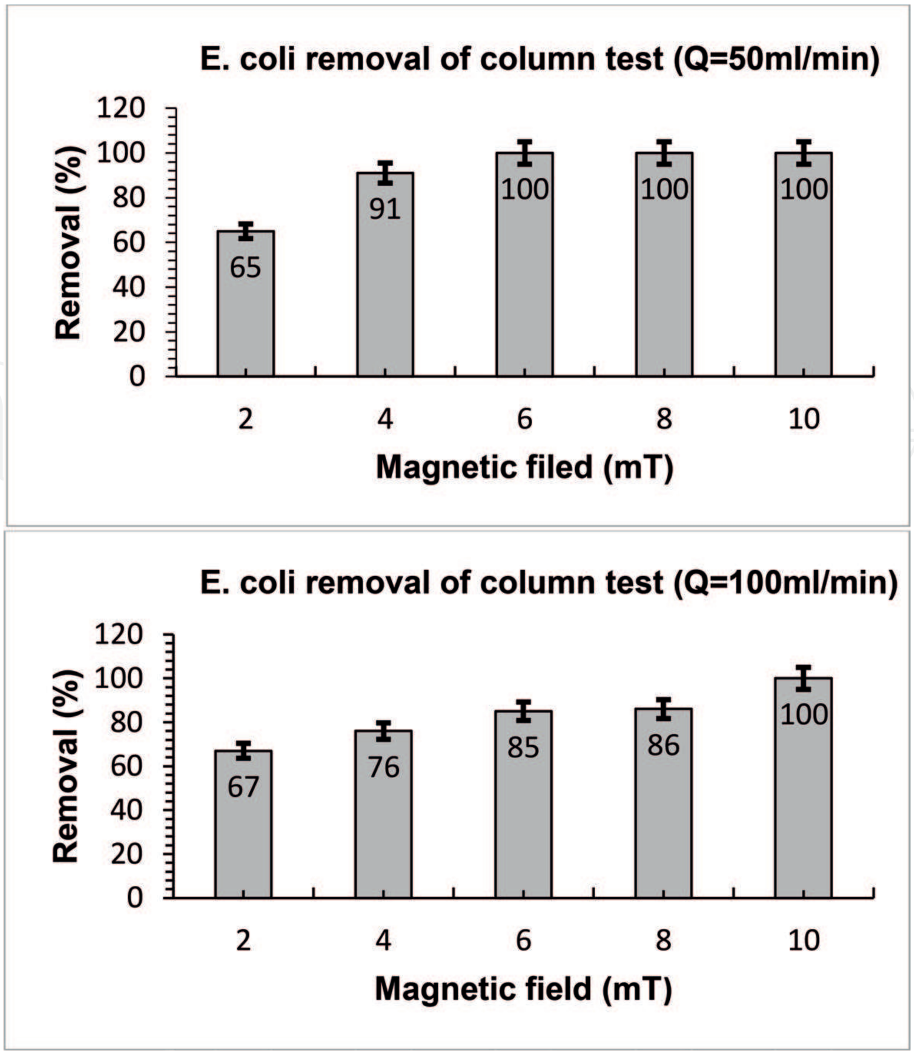

Figure 6.
Percentage of E. coli removal of column test (⌀ = 50 mm) for Q_1 *and* Q_2.

E. coli removal for Q_2 was 67% at 2 mT, and 100% of removal at 10 mT of magnetic field exposure. These results indicated that the *E. coli* in the sample of water that was exposed to the LF-EMF was statistically significantly decreased. The magnetic intensity of the LF-EMF changed the characteristic responses for *E. coli* bacteria [24].

From **Figure 6**, the results obtained demonstrated that column test achieved 100% *E. coli* removal, which increased with the increase of magnetic field exposure at Q_1 and Q_2. These results indicated that the magnetic field intensity was affected by the surface area of the coiled column. The 50 mm diameter of column test was effective for *E. coli* removal by LF-EMF exposure. This situation is possibly due to the influence of magnetic flux at various flow velocities, where the magnetic field killed the *E. coli* during the exposure at the surface area of the column. Thus, these results indicated that the removal of *E. coli* in column test was 100%, and also showed that the increase of *E. coli* removal is dependent on the increase in intensity of magnetic field along with other parameters of the column.

3.2 Effect of contact time in column test

In order to investigate the effect of LF-EMF exposure for varying durations of 2–6 hours on the removal of *E. coli*, the treatment conditions of exposure intensity were varied from 2 to 10 mT LF-EMF in column test. **Figure 7** illustrates the experimental results of the LF-EMF exposure hourly. The results demonstrated that the removal of *E. coli* approximately increased with the longer of exposure time. The

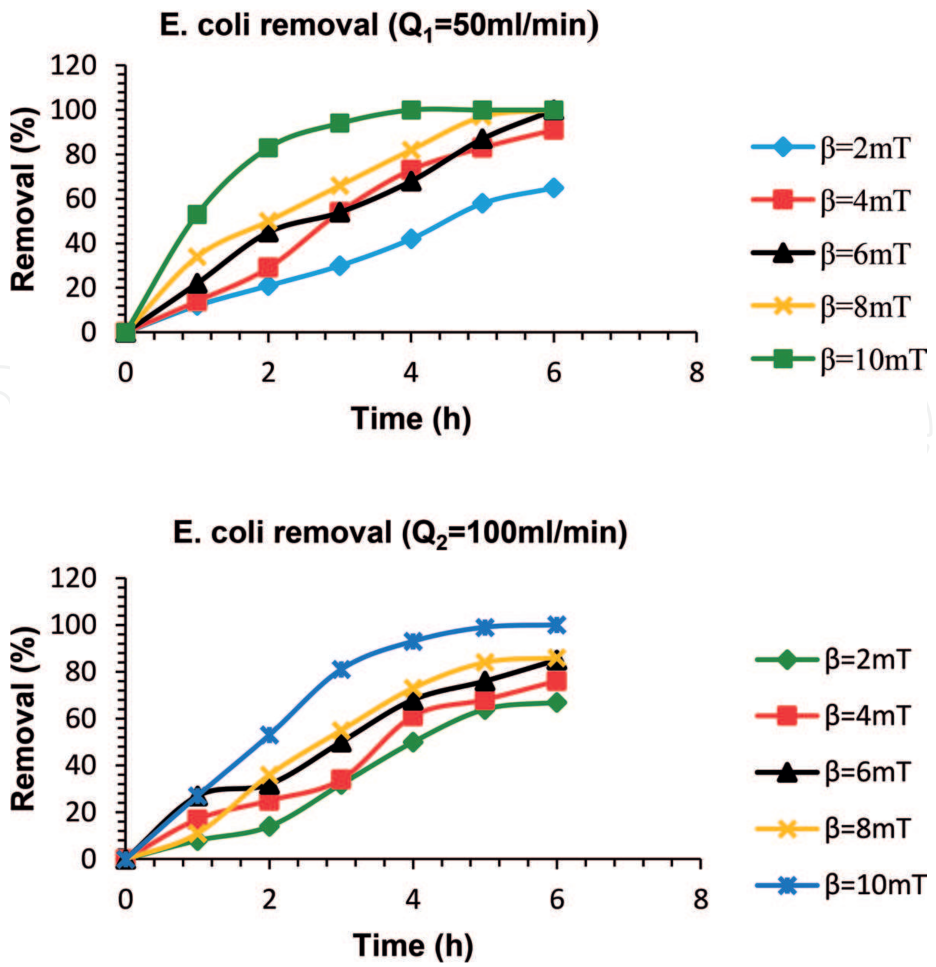

Figure 7.
Effect of time on removal of E. coli (Ø = 50 mm).

percentages of removal in column test achieved 100% at 4 hours of treatment at 10 mT of magnetic field intensity at Q_1 and Q_2. **Figure 7** is seen below.

The optimal time of magnetic field exposure on column test for *E. coli* removal is shown in **Figure 7**, which was at 4–6 hours exposure for both Q_1 and Q_2. The removal was 100% from 4 to 6 hours of 10 mT of LF-EMF exposure. These results indicated that the velocity (V) of water samples through column test was effective. Therefore, the removal rates of *E. coli* were constant after 4 hours of contact time with the magnetic field for Q_1 and Q_2. The magnetic field decreased the concentration of *E. coli*, and thus suggests that it affects the behaviour of *E. coli*. Strašák et al. reported that the inhibitory effects on *E. coli* concentration were increased with length of exposure [55]. Also Gaafat et al. applied extremely LF-EMF for 6 and 16 hours on the *E. coli*, and found that an exposure period of 6 hours decreased the concentration of *E. coli*, but after a 16-hour exposure period, they became more resistant towards it.

The effect of the exposure to LF-EMF at 2–10 mT on *E. coli* removal was determined by experimental results performed on the entire data for column test with water flowrates of Q_1 and Q_2. This effect generally depended on the magnetic field intensity and time of exposure [56], whereby the significant effect on *E. coli* removal was increased according to exposure time. From the experimental study, the R^2 results gave practical importance on exposure time for the removal of *E. coli*. From the results, it was found that the removal of *E. coli* and exposure time on column test were significantly correlated with high R^2 values for 2–8 mT of LF-EMF. However, at 10 mT of magnetic field intensity, the non-linear regression with polynomial R^2 at second order for Q_1 was 0.9721, while R^2 for Q_2 was 0.9958. These results showed that the *E. coli* removal at 10 mT exposure was 100% after 4 hours of exposure.

4. Conclusion

The ability of LF-EMFs to remove or decrease the concentration of *E. coli* in the river water samples was successfully demonstrated in this study. Based on the results, LF-EMFs were able to kill a part of the *E. coli*, and decreased the concentration by magnetic field exposure. From this study, the LF-EMF proved its capability to remove and control the growth of *E. coli* with magnetic field exposure. The effect of the magnetic field in the removal of *E. coli* by using an LF-EMF column model was validated with experimental results. Initially, simulations were carried out to study and design the magnetic field generating system, and compare the results with previous experiments. This result indicates that the application of the LF-EMF coiled column with a magnetic field at 6 mT was able to remove 100% of *E. coli*. The surface area and volume of the column induced changes in the percentage of *E. coli* removal. Therefore, it was found that the LF-EMF column test was effective column size to remove *E. coli* from the water. Data from the monitoring study for the RBF tube well showed low concentrations of *E. coli* during the wet and dry seasons. Thus, the result showed the suitability of LF-EMF column application in RBF as an alternative technique to control *E. coli* growth. Other than that, LF-EMF technology, as a non-chemical and non-ionising technique, was proposed in this study to increase the quality of water in RBF especially during the wet season. Some technical and fundamental principles related to the application of this technique provided valuable information about its capabilities in drinking water treatment applications, and at the same time, provided other opportunities for further research.

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