Environmental Engineering and Management Journal

May 2021, Vol. 20, No. 5, 749-767
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

“Gheorghe Asachi” Technical University of Iasi, Romania

EVALUATION OF PATHOGEN CONTROL PROCESSES AND METHODS FOR WASTEWATER EFFLUENTS DISCHARGED INTO THE ENVIRONMENT

Abdul Samad Ganiyu[1], Adil Ashraf[2*], Racchana Ramamurthy[2]

[1]*School of Civil Engineering, University of Leeds, LS2 9JT Leeds, United Kingdom*
[2]*Department of Environmental Engineering and Water Technology, IHE Delft Institute for Water Education,*
PO Box 3015, 2601 DA Delft, The Netherlands

Abstract

Surface water protection and sustainability is a vital move to enhance public health and ensure food and water security. Pathogen containing wastewater when discharged into water bodies, affects the water quality and poses health risks to the intended users. Even though various disinfection methods of domestic wastewater exist for pathogen control, much work has not been done to compare and ascertain the most effective method(s). A systematic literature review has therefore been conducted on the various available disinfection methods that have been evaluated in laboratory or on pilot scales or employed in full-scale wastewater treatment plants. Approximately 21% of the disinfection studies were conducted at full-scale. The technologies identified included advanced oxidation, microwave-induced electrodeless UV irradiation, ozonation and filtration, tin oxide anode, UV irradiation and peracetic acid. Generally, the combined technologies proved to be more effective than when used on their own. UV irradiation processes or their combination was the most frequently applied wastewater disinfectant method. Many of the disinfection processes proved effective in inactivating some of the pathogens and indicator organisms such as *E. coli*, total coliforms, *C. perfringens*, *Enterococci* and enteric viruses. Nearly all the disinfection methods were able to reduce *E. coli* and total coliforms.

Key words: disinfection, inactivation, pathogen, reduction, sewage, wastewater

Received: June, 2020; Revised final: July, 2020; Accepted: October, 2020; Published in final edited form: May, 2021

1. Introduction

The unceasing rise in global population subsequently put greater pressure on the available water resources (Bozorg-Haddad et al., 2020; Ibrahim et al., 2020). The increasing demand for water resources has resulted in its over-exploitation in the 21st century (Okoh et al., 2007). The global community faces water quality challenges due to urbanization, industrialization, inefficient wastewater management systems, and agricultural activities (Ashraf et al., 2020; United Nations [UN]-Water, 2015). An estimate of about one-third of the global freshwater usage comes from surface water resources (Edokpayi et al., 2017; Jonnalagadda and Mhere, 2001); most of these are used as discharge points for domestic and industrial wastes (Edokpayi et al., 2017). The World Commission highlighted that global human health and the ecosystem are at high risk due to the high rate of river pollution and depletion (Hello and Jaeel, 2014). It was estimated that about 9.5 million cubic meters of human excreta and 900 million cubic meters of wastewater are produced globally on a daily basis, and more than 80% of the global wastewater produced is illicitly discharged into the environment untreated (UNEP, 2016).

More than half of the world’s rivers, lakes and coastal waters are severely polluted by discharging untreated wastewater emanating from industries, residents and agriculture, containing large numbers of fecal bacteria (UNEP, 2002). Most often, industrial and residential wastewater containing pathogenic

---

[*] Author to whom all correspondence should be addressed: e-mail: ashraf_adil@outlook.com; Phone: +447741919998

organisms are released into the nearby waters posing huge health hazards to the water users, which in turn cause thousands of deaths on a daily basis and millions also suffering from waterborne diseases due to this (Hello and Jaeel, 2014).

Pathogens are organisms that can cause disease or illness within their hosts (Godfree, 2003). They can be found in the wastewater discharge from residential, industries or a wastewater treatment plant. The pathogen containing wastewater when discharged into water bodies, affects the water quality and poses health risks (Afzal et al., 2018; Toze, 1997; Yang et al., 2020). Different kinds of pathogens found in wastewater include viruses, fungi, bacteria, helminths and protozoans (Michael and Melvin, 2005). These are microbial pathogens and are said to be responsible for most of the waterborne diseases which are usually transmitted when using infested water for drinking or bathing. Many illnesses such as typhoid fever, dysentery, diarrhea, shigellosis and cholera are caused by these pathogens (Ajonina et al., 2015). These organisms cause the death of thousands of people every year in poor sanitation areas (Tchobanoglous et al., 2003). In spite of the current water and wastewater treatment technologies, pathogens caused illnesses are still among the major challenges across the globe (Saxena et al., 2020; Zhou and Smith, 2002).

Surface water protection and sustainability is a vital move to enhance public health and ensure food and water security. Water resources serve as a source of drinking water, provide employment for farmers and fishermen for irrigating crops and for fishing respectively. Surface waters are also used for swimming and for tourist attractions.

The Sustainable Development Goal (SDG) 6.3 aims to ameliorate globally the water quality and reduce the amount of polluted wastewater discharged into water bodies by 2030. The SDG also aims to protect and restore by 2020 every water-related ecosystem such as rivers, lakes and wetlands. Several pathogen control processes including membrane filtration, chlorination and ultraviolet light are used to polish wastewater prior to discharge (LeChevallier and Au, 2004). Even though various disinfection methods of domestic wastewater exist, much work has not been done to compare and ascertain the most effective method(s).

The present study has been conducted to evaluate the various wastewater disinfection processes that are applied in effluent discharges from a sewage treatment plant into open water systems, and to deduce the suitable disinfection methods that can be employed to treat different types of wastewaters. This work is the first attempt in reviewing systematically the disinfection processes that can be applied in wastewater treatment plant prior to effluent discharges. With a better understanding of the pathogen control processes, this research will help the industry/government policymakers in devising methods to restore the contaminated water resources.

2. Methodology

2.1. Data sources

The data sources considered for this literature review are well-known electronic databases; Web of Science, Engineering Village, and Scopus. Other sources such as Google Scholar, textbooks, and review of reference lists of the relevant retrieved articles were also outreached.

2.2. Literature search strategy

The literature searches were systematically conducted by focusing on keywords aspect and search terms that are directly related to the research question. The articles or abstract of articles that contained enough and comprehensive terms or words as in Table 1 and additionally correspond to the research topic were selected for further review, whilst the rest were discarded. This initial search processes yielded a total output of 85,234 research papers from the three databases; out of which 4,069, 30,633, and 50,532 documents were respectively obtained from the initial search of Engineering Village, Web of Science and Scopus, and were subsequently refined downwards as seen in Fig. 1.

Several published papers were rejected through refining by inserting further keywords to narrow the research question. Some articles were rejected straightaway because they contained titles or keywords that were completely irrelevant to answer the research topic in question for instance, “infection related to health care in an adult intensive care unit” etc. In addition to this, textbooks such as Wastewater Engineering, Treatment and Reuse; Water and Wastewater Microbiology; and Water Treatment Plants, Planning, Design, and Operation were used to support this review and to help identify other authors’ works that are related to the research topic.

2.3. Search limits and search terms

For this review, only published articles written in English Language were considered and the date of publication of articles was not limited during the search. This was to enable a general and wider search to minimize bias and to ensure a comprehensive understanding of existing wastewater pathogens disinfection processes and the progress made till date. Following the initial search, further screening using the eligibility and exclusion criteria (Table 2) of the identified papers were undertaken to segregate and/or include the potential articles that were specific and indeed relevant to the research topic.

After a careful sifting and evaluation, a total of 50, 24, and 82 articles from Engineering Village, Web of Science and Scopus were respectively retained for further review based on the pre-determined inclusion criteria. A total of 60 research papers were retained for detail review by abstract and full text.

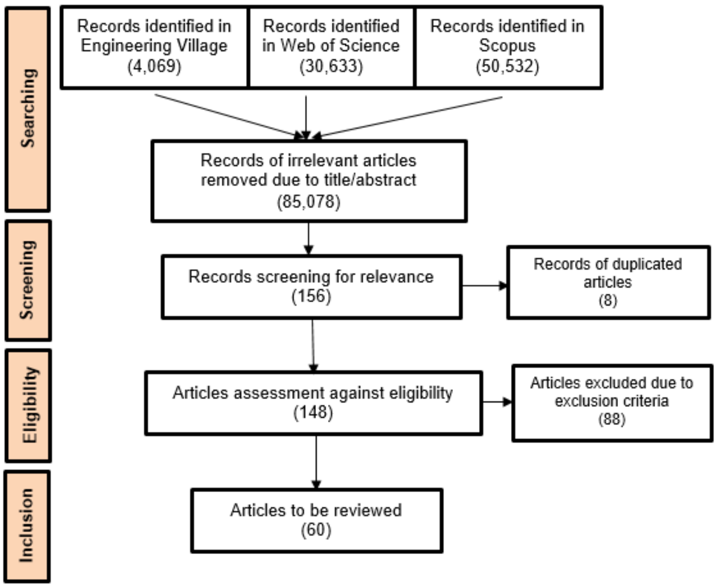


Fig. 1. Flow diagram of the systematic review process (based on Moher et al., 2009)

Table 1. Search terms/keywords used in the electronic databases systematic search

Keywords	*Databases*		
	Engineering Village	*Web of Science*	*Scopus*
Disinfection	4,069	30,633	50,532
AND Wastewater	608	2,946	10,764
AND Effluent	200	1,500	4,972
AND Municipal	50	433	2,422
AND Domestic	-	24	573
AND Pathogens	-	-	236
AND Sewage	-	-	196
AND Reduction	-	-	117
AND Inactivation	-	-	82

Table 2. Eligibility and exclusion criteria

No.	*Eligibility Criteria*
1	Studies that talk about the efficacy of wastewater disinfection process(es)
2	Studies that compare the effectiveness of disinfection or pathogens inactivation processes
No.	*Exclusion Criteria*
1	Articles published in any language other than English
2	Articles not dealing with microorganisms' disinfection/reduction/removal
3	Research articles that do not talk about wastewater microbes/pathogens
4	Studies not dealing with municipal/domestic/sewage wastewater or effluent disinfection

2.4. Critical review and evaluation

A critical review and evaluation of the finally selected literature were undertaken by carefully reading the full text of the articles to understand the author(s) argument in order to make a relevant evaluation. The review was done conceptually and methodologically such that all studies having similar ideologies or methods are grouped together, for instance, the advanced oxidation processes (AOPs).

3. Wastewater pathogens control and inactivation processes

Pathogenic organisms present in wastewater can be controlled and eradicated by several available disinfection methods. The challenges are that getting a single method to control effectively the various pathogenic and indicator organisms found in wastewater have always been a challenge to deal with since different wastewater pathogens may respond or behave differently under similar or different conditions. Since the germicidal effects of disinfectants depend on several factors including the wastewater characteristics and their choices of selection for effective disinfection of microorganisms is somewhat a complex task to do with (Acher et al., 1997). There is a need to evaluate and ascertain the effective wastewater disinfection methods in terms of effectiveness in pathogens reduction and inactivation to help choose the right option(s) for disinfection of domestic wastewaters from sewage treatment works.

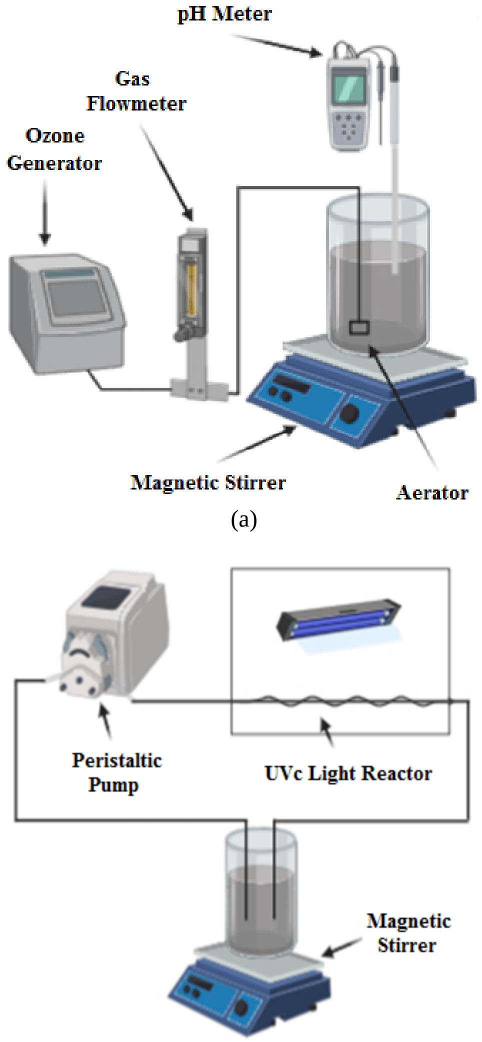
However, there have been several environmental and safety concerns in recent years in using certain disinfection methods such as chlorination due to the formation of undesirable disinfection by-products (DBP) as well as other costs related with improvement to meet the stringent regulatory standards governing the onsite use, handling and transportation (Qasim, 1985). These concerns among other factors continue to raise the interest of researchers to investigate the alternative disinfection methods (Loge et al., 2006). Globally, chlorination, ozonation and ultraviolet (UV) treatment technologies are the most commonly used disinfection processes (Hijnen et al., 2006). The available wastewater disinfection technologies were systematically and critically reviewed and classified under the following broader headings of disinfection processes; AOPs, microwave-induced electrodeless ultraviolet (MW-EUV) irradiation, tin oxide anode, peracetic acid (PAA), physical/chemical-natural disinfection processes, disinfection using ferrate (VI) ion, electron beam (EB) irradiation, disinfection using UV irradiation, ozonation and filtration.

3.1. AOPs

This is an advanced technology employed in the treatment of complex wastewater contaminated with organic and inorganic pollutants as well as for the removal of micro contaminants and the deactivation of pathogenic microorganisms; it involves the use of the different oxidation processes or their combination such as O_3, O_3/H_2O_2, UV/H_2O_2 (Malvestiti and Dantas, 2018), and UV/O_3, Fenton's reagent and electrode AOPs (Loge et al., 2006; Ma et al., 2020).

The AOPs referred to as the aqueous phase chemical oxidation make use of the action of the highly oxidizing potential of hydroxyl free radical ($HO^{\cdot}$) producing substances (UV radiation, ozone, chlorine, and oxygen etc.) to degrade the target refractory compounds that are difficult to remove using the conventional oxidation methods (Cesaro et al., 2013; Tchobanoglous et al., 2003; Rosenfeldt et al., 2006). The AOPs have been in existence and used for water treatment and disinfection for many decades (Giannakis et al., 2015). Studies have also shown that they are effective against emerging pollutants (Khan et al., 2020). Many researchers have conducted various performance studies of the AOPs which are to be critically reviewed. It is, however, a difficult task to compare the inactivation performances of various AOPs due to their different physical and chemical processes, operating conditions and sources of generating the $OH^{\cdot}$ radicals (Contreras et al., 2002; Rosenfeldt et al., 2006).

According to Malvestiti and Dantas (2018), all the three forms of oxidation processes; O_3 (~4.6-log), O_3/H_2O_2 (~5-log) and UV/H_2O_2 (~5-log) reductions were effective in the inactivation of *Escherichia coli* (*E. coli*) and total coliforms in the secondary effluent within 30 min of the process. However, they discovered that the presence of carbonate and nitrate affected the disinfection process in the ozone set up (Fig. 2a) such that nitrate caused to lower (by ~2-log) the disinfection rate whilst carbonate caused a higher reduction in penetration (Malvestiti and Dantas, 2018).



(a)

(b)

Fig. 2. (a) Schematics of the ozone reactor; and (b) UV/H_2O_2 reactor (adapted from Malvestiti and Dantas, 2018)

It was concluded that O_3/H_2O_2 and UV/H_2O_2 processes performed better than using ozone alone. However, the addition of H_2O_2 to the ozonation process promoted the hydroxyl radical ($HO^{\cdot}$) formation which increased the disinfection rate and further improved the inactivation of *E. coli* in the presence of the scavengers; similar performance occurred with the combined UV/H_2O_2 process (Fig. 2b).

In brief, the inclusion of hydrogen peroxide (H_2O_2) in a higher concentration coupled with the ozonation process caused a reduction in the scavenging action of carbonate and nitrate which favoured mostly the inactivation of total coliform. Complete inactivation of *E. coli* was said can be enhanced by doubling the ozone dose to lessen the action of the carbonate and nitrate (Malvestiti and Dantas, 2018). This means that the application of a single conventional method for inactivation is likely not as effective as the combination. Malvestiti and Dantas (2018) in their studies did not mention the purity level of ozone gas used or its source and/or how it was generated. They did not also consider the post disinfection measures to manage the off-gases from the contact chamber that can potentially contain residual ozone which is toxic and an irritant.

The ozone dose (11 mg/L) used in the ozonation experiment could have been varied to better ascertain the influence of the carbonate and nitrate; as previous research reported ozone dose between 3-40 mg/L can be used to inactivate total coliforms (Bustos et al., 2014), and Verma et al. (2016) considered the ozone dose between 30 and 33 mg/L as the effectively transferred ozone dose with the potential to reduce significantly resistant coliforms and cause partial reduction of remnant organic matter. Verma et al. (2016) utilised 30 mg/L ozone dose to effectively reduce *E. coli*, *Enterobacter*, *Klebsiella*, *Serratia*, *Citrobacter* and total coliforms to as low as 1,000 CFU/100 mL. Aslan et al. (2018) investigated the inactivation of antibiotic-resistant *E. coli* in an effluent using a combination of UV followed by chlorination which significantly reduced the *E. coli* with an average of 5.2-log and 1.1-log for UV and chlorination respectively. As mentioned in Malvestiti and Dantas (2018), a combination of two or more disinfection methods proved more successful than a single method since the total reductions caused by two or more combined methods outweighed the individual method. The presence of certain contaminants such as bicarbonate could, however, affect the UV inactivation of the antibiotic-resistant *E. coli*. According to Loge et al. (2006), the presence of carbonate and bicarbonate which are scavengers of hydroxyl radicals in wastewater could reduce $HO^{\cdot}$ by up to four orders of magnitude.

Hence, the application of both UV/H_2O_2 or UV/Chlorination enhanced the reduction of *E. coli* than when applied individually. It is difficult to compare UV/H_2O_2 and UV/Chlorination due to the difference in the properties of the samples used for the experiment. The summary of the antibiotic-resistant removal of *E. coli* from the initial presumptive concentration of $2.5 \times 10^7 \pm 1.36 \times 10^7$ CFU/100 mL in the wastewater shows that the combined methods (UV + chlorination) resulted in the highest removal of *E. coli* relative to the single applied method.

Liberti and Notarnicola (1999) conducted a study to compare the disinfection performance of UV rays, peracetic acid and ozone to disinfect domestic wastewater. Three different types of effluents namely secondary, clarified and clarified-filtered effluents of increasing quality were utilised for this study. As may be expected, pathogens reduction from the clarified or clarified-filtered effluent yielded better results as it contains fewer pollutants relative to the secondary effluent. The disinfection of clarified or clarified-filtered effluent with a UV dose of 100 and 160 mW/cm^2 respectively agreed with the Italian standards (2 CFU/100 mL) of total coliforms for unrestricted reuse of municipal wastewater in agriculture. UV and PAA achieved more than 5-log while ozone achieved close to 4-log reductions. The helminth eggs were also reported to be effectively removed by the clarification and filtration units and all the three methods effectively reduced *Pseudomonas aeruginosa*. They also reported that UV radiation was effective towards parasites such as *Giardia lamblia cysts* and *Cryptosporidium parvum oocysts*, and ozone was effective towards *Giardia* only whilst PAA did not yield any good effects towards both parasites (Liberti and Notarnicola, 1999). This result obtained using PAA disinfection was contrary to that obtained by Jensen et al. (2013) which could be due to the difference in the type of microorganisms of considerations or probably due to the difference in effluent characteristics.

3.2. MW-EUV irradiation

This technology employs the operation of a microwave and UV irradiation to destroy microorganisms' content of domestic effluents. The disinfection using only UV irradiation is not considered effective hence it was synergised with a microwave process (Zhang et al., 2017).

Zhang et al. (2017) decided to test the combination of microwave technique and UV irradiation for disinfection as a supplement to the UV process. A modified homemade microwave (Fig. 3) with a variable output power was used for the experiment. Their experiment showed that the MW-EUV produced better results than using UV or microwave irradiation alone under optimal microwave power of 600 W.

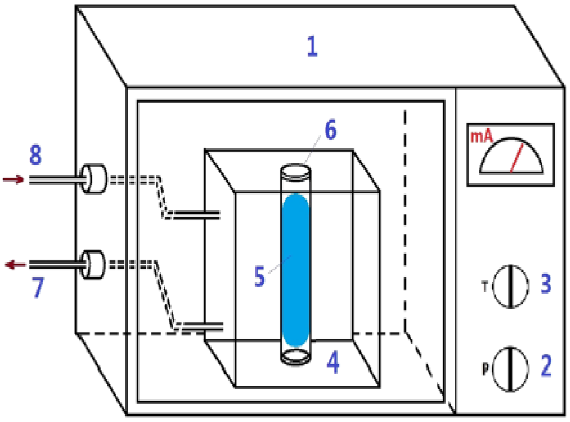


Fig. 3. Schematic of the MW-EUV irradiation setup: (1) microwave oven; (2) power button; (3) time button; (4) disinfection reactor; (5) electrodeless UV lamp; (6) UV lamp holder; (7) water outlet; (8) water inlet (Zhang et al., 2017)

A higher disinfection rate was achieved in the MW-EUV when the microwave power was increased, so the higher the microwave power (600 W) the stronger the light intensity and a corresponding increase in its sterilisation ability at 254 nm (Zhang et al., 2017). Zhang et al. (2017) also indicated that the inactivation of bacteria by the MW-EUV irradiation is more effective when the contact time increases and at 25s-time length has caused a reduction in the active total coliforms (3.8 × 10^5 CFU/L) and the total bacteria count (4.3 × 10^3 CFU/mL) to 2 CFU/L and 2 CFU/mL respectively. Nevertheless, this experiment conducted by Zhang et al. (2017) needed further assessment for its commercial applicability.

Cheng et al. (2020) attempted to test the bactericidal effect of MW/UV and MW/UV/O_3 reactors by using domestic sewage. The reactions of UV/O_3 are provided as Eqs. (1-3). They found out that the water quality after treatment by MW/UV/O_3 reactor contained less than 3 CFU/L of *E. coli* and the bactericidal rate exceeded 99.99%. Microwave power and influent turbidity were the major impacting factors in the sterilisation effect of MW/UV reactor. The terminal turbidity of MW/UV reactor for disinfection is 40 NTU. For the best sterilisation efficiency, the raw water turbidity should be less than 8 NTU and if the influent turbidity is high (>10 NTU), pretreatment (filtration) is required to lessen the turbidity and improve the bactericidal impact.

$$O_3 + H_2O + hv \rightarrow O_2 \_ H_2O_2 \qquad (1)$$

$$O_3 + H_2O + hv \rightarrow O_2 + 2OH \qquad (2)$$

$$H_2O_2 + hv \rightarrow 2OH \qquad (3)$$

3.3. Tin oxide anode (SnO_2)

The application of tin oxide anodes was studied to effectively disinfect wastewater effluent using the hydroxyl radical generated as a disinfecting oxidizing agent in the process (Watts et al., 2008). The hydroxyl radical is generated at the anode surface (Eq. 4 and 5) and dipped into the water by applying a direct current onto it (Loge et al., 2006; Watts et al., 2008).

$$MO_x + H_2O + hv \rightarrow MO_x(OH)_{ads} + H^+ + e^- \qquad (4)$$

$$MO_x(OH)_{ads} \rightarrow 0.5O_2 + MO_x + H^+ + e^- \qquad (5)$$

The efficacy to disinfect wastewater using this approach was investigated by Loge et al. (2006). The tin oxide anode set up comprising of anodes and cathodes (made of 6.35 mm iron and steel) were assembled with other parts as seen in Fig. 4. Following this experiment, Loge et al. (2006) concluded to achieve a significant and effective inactivation of total coliform bacteria using the bench-scale tin oxide disinfection method, better than UV and other disinfection methods.

The specific characteristics of the effluent can affect the inactivation rate of tin oxide anode by reducing the relative activity of the hydroxyl radicals or other active species (Loge et al., 2006). However, the specific characteristics of the effluent samples used for these tests were not given. This implies that the required effluent quality that can be treated by the tin oxide anode methods should be ascertained. The complexity and safety nature of this method need to be well understood as it involves the complex application of electrical current. To use a tin oxide anode system to disinfect a secondary effluent, containing coliform bacteria with a concentration of 2 × 10^6 MPN/100 mL and with a discharge standard of 23 MPN/100 mL would require a dose of 9.2 pM.s, which corresponds to a 5-log reduction in coliform bacteria (Loge et al., 2006).

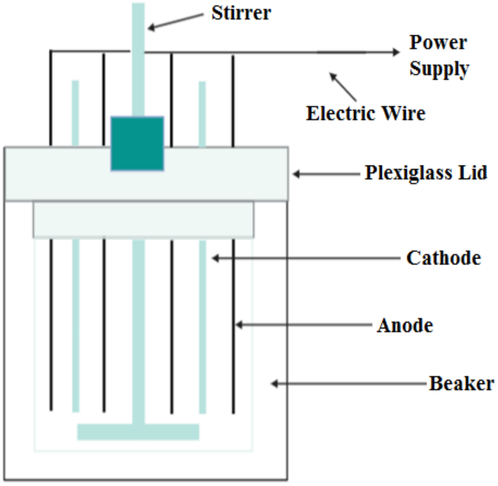


Fig. 4. Depiction of the pilot study of tin oxide anode disinfection system (based on Loge et al., 2006)

A cost-benefit analysis of the tin oxide anode system was performed against UV and chlorination and the result showed that tin oxide anode disinfection system is relatively cost-efficient and a promising option to conventional methods with a common yardstick of discharge requirement of 23 MPN/100 mL at 3,785 m^3/d (Loge et al., 2006).

3.4. PAA and UV-C disinfection techniques

PAA is a promising chemical disinfectant with great antimicrobial properties against a wide spectrum of microorganisms and forms negligible byproducts (Campo et al., 2020). These are alternative sewage disinfection technologies (PAA and UV-C) that were being investigated for applying in the Arctic environment due to the challenges and cost of adapting the conventional disinfection systems. The Arctic environment is characterised by its very cold temperature and scattered settlement (Jensen et al., 2013). The concentration of total coliforms in the effluent samples were weak, the mid concentration of *E. coli* and very high faecal *streptococci* and *enterococci* (Jensen et al., 2013).

According to Jensen et al. (2013) the results from the aftermath analysis (with particulates removal >60 µm) showed the ability of the PAA and UV-C disinfection to significantly reduced the number of gram-negative and gram-positive bacteria, with a maximum reduction in coliforms and *enterococci* by order of 2 to 3 using 25 mg/L PAA; *E. coli* reduction exceeding 6 size orders. Using a UV dose of 37 mJ/cm^2 could effectively reduce *enterococci* with an order of more than 4 (Jensen et al., 2013).

The PAA method alone was considered to be very effective against enteric bacteria and to some extent, bacterial spores, viruses and protozoa cysts (Kitis, 2004; De Luca et al., 2008); however, the optimum PAA dose and contact time for a given wastewater type were not stated (Bonetta et al., 2017). Jensen et al. (2013) in their study produced the parameters of the sewage after filtration to know the quality level of the filtrate that was used in the experiments. The two methods could have also been combined to further ascertain their effectiveness. PAA was also compared with chlorine dioxide disinfection by Stampi et al. (2002), even though PAA was found to be less efficient than chlorine dioxide it can be offered as an alternative chemical disinfectant. Similarly, PAA was compared with performic acid (PFA) in a study conducted by Campo et al. (2020). The results showed that PFA was more effective than PAA in secondary effluent wastewater as complete log removal was achieved with PFA ICT (integral estimate of the time-dependent residual disinfectant concentration) of ∼15 mg.min/L compared to PAA ICT of >60 mg.min/L but proposed both disinfectants as effective altenative to chlorine.

PAA was quite effective against the enteric faecal indicator bacteria as reported by (Kitis, 2004; Luca et al., 2008). However, the result of the study obtained by Stampi et al. (2002) was contrary to the point that PAA is more effective than chlorine dioxide, attributed to the presence of suspended solids that impacted the chlorine dioxide products. Hassaballah et al. (2020) studied the inactivation of *E. coli, Enterococcus spp.*, somatic coliphage, and *Cryptosporidium parvum* oocysts by NaOCl, PAA, and PAA plus UV in secondary wastewater from various utilities. The combined utilisation of PAA (20 mg.min/l) and UV (14.7 mJ/cm^2) accomplished the same or higher log reductions than PAA only or UV only for *E. coli, Enterococcus spp.* and somatic coliphage and log reductions by PAA were higher when computed at 24 h than at 10 min after PAA treatment while only the log reduction of *Enterococcus spp.* by PAA plus UV were higher when enumerated at 24 h than at 10 min.

The inactivation of human enteric viruses from two effluent samples using UV units was investigated by Qiu et al. (2018). The concentrations of the enteric viruses (*rotavirus, astrovirus, norovirus, reovirus, enteroviruses, sapovirus, JC virus and adenoviruses*) were 98% and 76% in the pre-UV and post-UV effluent samples, equivalent to 1.46-1.67-log reduction for the two effluent samples. Due to the differences in the types of microbial pathogens investigated by Qiu et al. (2018) and Jensen et al. (2013), a direct comparison would not be effectuated (Acher et al., 1997). In 2001, Stampi et al. conducted a study to evaluate the effectiveness of PAA for sewage effluent disinfection prior to discharge into surface water. The results of their study reported an effective reduction of total coliforms and *E. coli* content of the sewage effluent from 10^7 MPN/mL to 10^2, and 10^6 MPN/100 mL to 702 MPN/100 mL of *enterococci* with a dose of between 1.5 to 2 mg/L for 20 min. It also showed the potential for reducing heterotrophic plate count by 52%. The result obtained by Stampi et al. (2001) yielded a higher order of 5-log reduction with a small PAA dose (2 mg/L) relative to that used (25 mg/L) by Jensen et al. (2013) which may be due to the different in atmospheric ambient conditions, that is, the efficiency of PAA as a disinfectant as used in Stampi et al. (2001) study increased with increasing temperature.

A study conducted by Bilotta and Daniel (2010) for microbiological control of domestic wastewater, involved installing a UV radiation in two stages in the whole treatment process; a pre-disinfection stage (installed after USAB reactor) and the final disinfection stage (installed after the biological filter) in a conventional wastewater treatment system. The configuration of their experimental setup is represented in Fig. 5 and samples were taken after 30 s of the stage 2 process.

Although, the results obtained in the studies conducted by Bilotta and Daniel (2010) proved effective in reducing *E. coli* (20 CFU/100 mL), total coliforms (80 CFU/100 mL) and coliphages (undetected) and are said to be in agreement with the Brazilian and WHO (World Health Organisation) standards, the specific effluent characteristics subjected to the two-stage disinfection units were not enumerated, as did in the experiment conducted by Jensen et al. (2013) in using PAA and UV-C disinfection systems. Bilotta and Daniel (2010) only focused on TSS and kept the concentration below 100 mg/L, however, other wastewater constituents including oil and grease, humic materials, manganese etc could potentially affect the efficiency of UV radiation (Liberti and Notarnicola, 1999; Tchobanoglous et al., 2003). De Sanctis et al. (2016) evaluated a lab-scale integration of a Sequencing Batch Biofilter Granular Reactor (SBBGR) with PAA or UV disinfection process to treat and disinfect raw domestic sewage. The SBBGR, besides being effective in reducing SS (5 mg/L), COD (32 mg/L), and nitrogen (10 mg/L). It was also observed that it effectively removed in log units these pathogens: 2.8 ± 0.8 *E. coli*; 3.8 ± 0.4 *Giardia lamblia*; 2.5 ± 0.7 total coliforms; 2.0 ± 0.3 *Clostridium perfringens*; 2.0 ± 0.4 *Cryptosporidium parvum*; and 1.7 ± 0.7 Somatic coliphages. The subsequent disinfection of the SBBGR effluent using a UV dose of 40 mJ/cm^2 or 1 mg/L PAA stirred for 30 min effectively lowered the *E. coli* content to below 10 CFU /100 mL. These results were in agreement with that obtained by Bilotta and Daniel (2010) for integrating a biological treatment unit with UV disinfection and is an effective disinfection combination. In another pilot study, De Sanctis et al. (2017) combined a sand filtration unit to enhance the performance of SBBGR. Up to 2.7 and 3.2-log units reduction of *C. perfringens and* somatic coliphage and 4.2-log units *E. coli* reduction were respectively achieved after sand filtration.

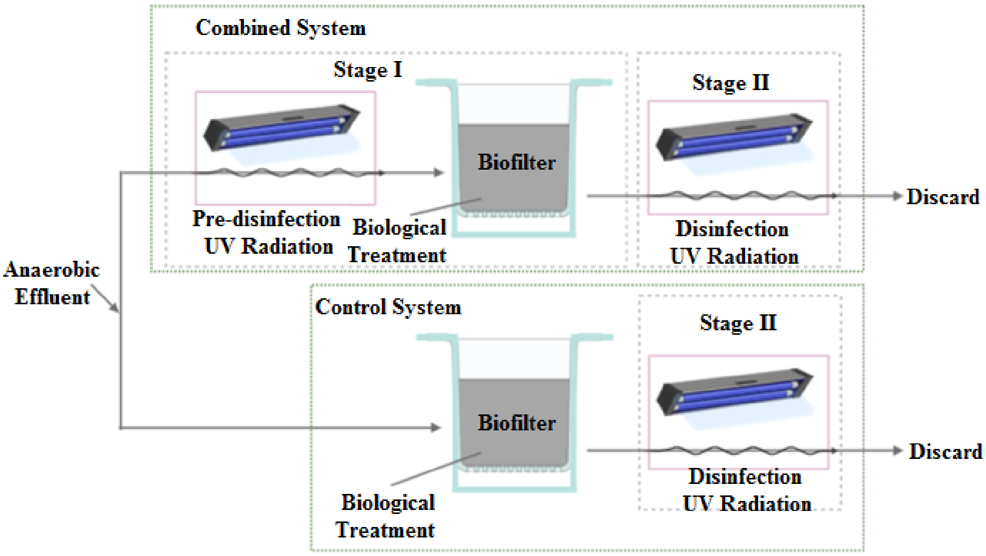


Fig. 5. Schematic of the two-stage disinfection systems (adapted from Bilotta and Daniel, 2010)

3.5. Physical/chemical-natural disinfection methods

Chemical disinfection treatment system (chlorination) is a widely used wastewater disinfection method due to its low cost and widely known technology, however, it is not effective to inactivate *Giardia* and *Cryptosporidium* (Lane and Lioyd, 2002). Besides the formation of chlorinated products, it has a high tendency to cause tank rupture and emission of harmful gases into the environment (Boorman et al., 1999; Watts et al., 2008). It also generates chlorination-resistant bacteria strains which pose a great challenge to this technology, hence creating an interest to consider integrating with other friendly disinfection options (Bonetta et al., 2017; Luukkonen et al., 2014). The use of chemical process (chlorination) followed by the natural treatment (constructed wetlands) for disinfection was considered relatively easy to operate and needed less energy than the regular conventional methods (Verlicchi et al., 2009).

Nevertheless, Verlicchi et al. (2009) conducted a study to inactivate microorganisms in wastewater meant for reuse or discharge using chemical treatment (NaClO) and natural process (chemical-natural disinfection system). They subjected the effluent obtained from the secondary treatment containing an average *E. coli* of 5.6 × 10^3 CFU/100 mL, suspended solids of 7 mg/L, and COD of 54 mg/L to the pilot plant of horizontal subsurface flow (HSF) beds setup as shown in Fig. 6. The pilot study consisted of three HSF cells of line A -filtration, line B-mild chlorination and line C-natural treatment. The final result showed a better removal of *E. coli* with less than 10 CFU/100 mL. This implies a good performance for the combined system in hotter than colder countries since the *E. coli* removal was 2.6-2.7 log-units. However, the concentration of other pathogenic indicator organisms (total coliforms) of importance in wastewater discharge ought to have been considered in their studies to understand the full efficiency and applicability of this method elsewhere.

Russo et al. (2019) in their studies combined constructed wetlands with UV or lagooning treatment systems to remove wastewater microbiological indicators specifically *E. coli*, *Enterococci* and total coliforms. An average of 1.5-log microbiological reduction through lagooning was achieved, whereas, the constructed wetlands systems (CWs) combined with UV achieved complete removal *of E. coli*, *C. perfringens* spores, somatic coliphage and massive reduction of other microbiological indicators. The following log reduction; 4, 4.4, 3.6 and ~1.4 respectively of *E. coli*, total coliforms, *Enterococci* and *C. perfringens* spores were removed by CWs and UV combined treatment systems. However, the *Enterococci* and total coliforms were not effectively removed by the two processes. The variations in the number of microorganisms removed may be attributed to changes in seasons (Russo et al., 2019). Kaliakatsos et al. (2019) examined the combination of two CWs; CWs1 and CWs2 coupled with sand filters to treat and disinfect primary wastewater contaminated with bacterial indicators (*E. coli,* total coliforms, *Enterococci*) and viruses (adenoviruses and enteroviruses).

The CWs were able to effectively achieve almost 3.2-4-log units (99%) bacterial removal for the CWs1 and 1.9-2.7-log units (89-98%) for the CWs2 systems. The adenoviruses were only slightly reduced with 2.5-log units for adenoviruses and 3.4-log units for *enteroviruses* in CWs1; whereas CWs2 respectively reduced 4.3 and 1.9-log units (Kaliakatsos et al., 2019). The low reduction in the viruses could be due to their high concentrations in the untreated primary wastewater. Zhou et al. (2016) applied an ultrasound system and chlorine dioxide (ClO_2) to disinfect faecal coliform with the aim of using the ultrasound influence to reduce the ClO_2 - consumption and simultaneous reduction of the DBPs.

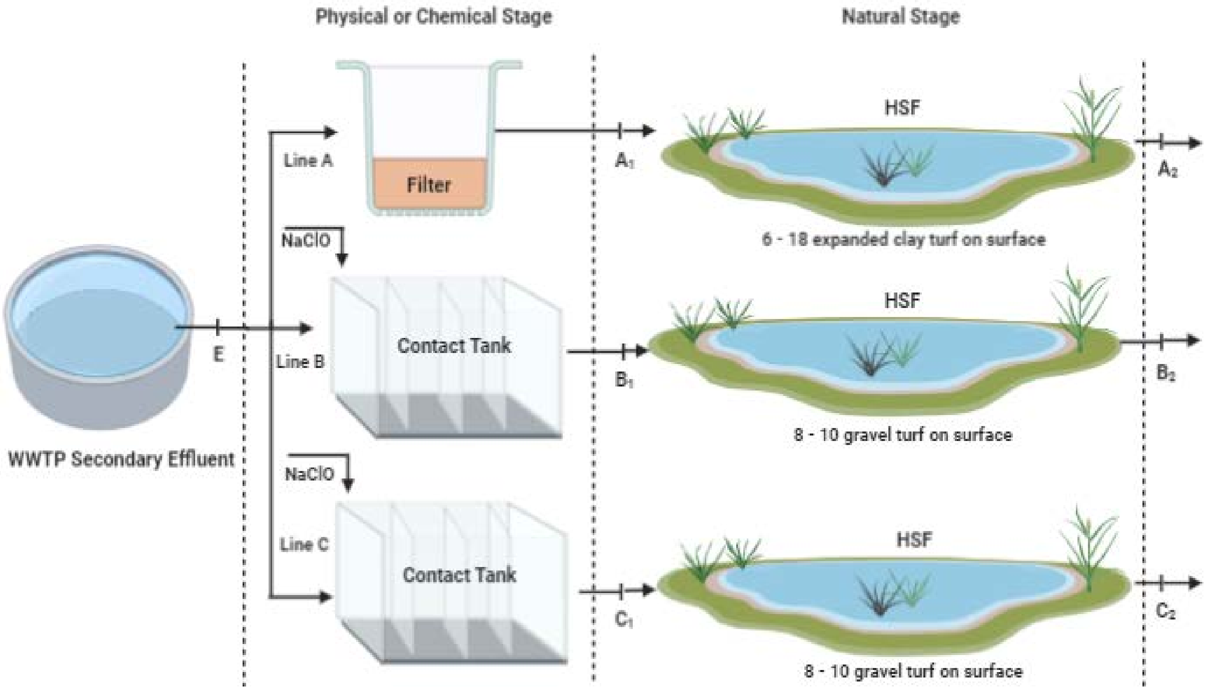


Fig. 6. Three schemes of chemical-natural pilot plant studies (based on Verlicchi et al., 2009)

Their results showed that the application of ultrasound with ClO_2 could reduce the ClO_2 consumption by half, hence an effluent discharge with 4.4-log unit faecal coliforms removal from initial of 10^6 CFU/L could be met by applying power density of 2.64 kJ/L and ClO_2 concentration of 1.5 mg/L. The inorganic DBPs (ClO^{2-} and ClO^{3-}) were also reported to have reduced significantly to about 1.1 and < 0.025 mg/L respectively. Comparing this result to that obtained by Verlicchi et al. (2009) showed a close removal efficiency for *E. coli* and faecal coliforms even though the methods applied were different.

3.6. Ferrate (VI) ion disinfection

Ferrate (VI) ion, FeO_4^{2-} has recently been considered as a potential disinfectant of water and wastewater due to its strong oxidising potential and concurrent generation of ferric coagulating species, which enables it to act as coagulant, oxidant and disinfectant (Ghernaout et al., 2011; Jiang, 2014). The general oxidation mechanism of Fe(VI) for the treatment of a contaminant is presented in Eq. (6) with the Fe(III) iron product ferric oxide in various states of hydration (Ghernaout et al., 2011). It was considered as the strongest disinfectant/oxidant among all others in the treatment of water and wastewater, however, the relative instability of ferrate (VI) solution and high production cost of solid ferrate (VI) stand as a challenge for its commercial implementation (Jiang, 2014). Jiang (2014) observed that ferrate (VI) was more effective than hypochlorite and that only a smaller dose (1.5 mg/L) of ferrate (VI) was required to disinfect raw sewage containing *E. coli* (4-log) and total coliforms between pH 6.8-7.2. Ferrate (VI) was also effective in the reduction of spore-forming bacteria and sulphide-reducing clostridia (Jiang, 2014). However, the detail tests of ferrate (VI) ion were not conducted by Jiang in his study to give a better understanding of its inactivation performance. Jiang (2014) based most on the removal of macro pollutants (pharmaceutical and personal care products (PPCPs) using ferrate (VI), which is not a focus of this review.

$$\begin{aligned} &aFe(VI)+bConta\min ant \rightarrow cFe(III)+dDe- \\ &-toxified\ \ Conta\min ant \end{aligned} \qquad (6)$$

3.7. EB irradiation

EB, another form of AOPs was used in the treatment and disinfection of various types of wastewater such as municipal and industrial. The EB is able to generate ozone and radiation that can be used for wastewater disinfection (Emami-Meibodi et al., 2016). The EB reactor is a highly sophisticated unit consisting of a rectangular cubic AISI 316 stainless steel with $1{,}404 \times 78 \times 75\ mm^3$ dimensions with a flow rate of 60 L/min as shown in Fig. 7. In the studies conducted by Emami-Meibodi et al. (2016) in using EB to disinfect municipal wastewater following a biological treatment resulted in reducing coliforms to more than 90% with a dose of 2-3 kGy and approximately 50% reduction in BOD and COD. It was observed that the turbidity of this effluent, 1.4 NTU was far lower than the effluent used by Zhang et al. (2017) and Malvestiti and Dantas (2018), 5.5 NTU and 63.1 NTU respectively that might have favoured the performance of the EB process which implies that effluent with very low turbidity or TSS was required for maximum reduction of coliforms, otherwise, increasing the dose above 3 kGy may further escalate the treatment cost since it was already reported that EB treatment method consumes high energy and also requires high capital investment (Emami-Meibodi et al., 2016).

3.8. UV irradiation, ozonation and filtration

An assessment to determine the disinfection performance of three disinfection methods; UV irradiation, ozonation and micro/ultrafiltration on the secondary effluent of a wastewater treatment plant were examined. The three treatment or disinfection processes have been considered sufficient for meeting WHO standards for wastewater reuse on farmland, public parks, and sports fields with less than 1,000 CFU/100 mL faecal coliforms of treated municipal wastewater (Luczkiewicz et al., 2011). These processes particularly ozonation can also be used in hospital wastewater treatment (Khan et al., 2019). Its utilisation has been endorsed in numerous nations due to its high biocidal viability in a wide antimicrobial range, high vulnerability and decomposition without leaving residues (Nahim-Granados et al., 2020).

Luczkiewicz et al. (2011) examined the efficiency of three disinfection process for their potential of reducing faecal coliforms and *Enterococcus spp*. from wastewater comprising 94.83% municipal wastewater, 5% industrial and 0.17% hospital wastewater with about 1.8×10^4 CFU/100 mL and 3.5×10^4 CFU/100 mL of faecal *enterococci* and faecal coliforms respectively. Their results proved that ultra/microfiltration effectively reduced more than 99% of faecal bacteria whilst the ozonation and UV irradiation respectively required a dose of more than 4 mg O_3/L and 10-20 mJ/cm^2 to attain faecal coliforms of 1,000 CFU/100 mL of treated wastewater. However, the transfer efficiency and contact time in ozonation is essential for effective disinfection (Tchobanoglous et al., 2003) but these parameters were not considered in this study. The frequency of cleaning or replacing the membrane filter to understand the throughput per given time was also not mentioned.

George et al. (2002) decided to determine and compare the faecal coliforms removal efficiency of each unit of wastewater treatment plants (WWTP) across 14 WWTP in France and Belgium. The treatment units assessed within these sewage treatment plants were activated sludge process, activated sludge process with nitrification, activated sludge process followed by biofiltration, activated sludge with nitrification and denitrification, series of 3 biofilters, lagooning and activated sludge, sand filtration and disinfection. The experimental results confirmed the combination of activated sludge, sand filtration and UV disinfection achieving a 3.7-log reduction; 0.78 by sand filtration and 2.91 reductions by UV to be the most effective in terms of coliforms removal among the series of wastewater treatment options in question, followed by the lagooning process.

The disinfection of municipal wastewater by a sensitised photo-oxidation was also investigated. The photo-oxidation reactor is often sensitised by titanium dioxide (TiO_2) which is the most commonly used semiconductor in photo-oxidation process since it is cost-effective, has a high photoactivity, insoluble and non-toxic (Li et al., 1996). TiO_2 is deliberated as one of the most commonly used nanomaterial for water treatment (Khan et al., 2012).

Li et al. (1996) applied a discovered alternative method of semiconductor-sensitised photo-oxidation to disinfect treated activated sludge secondary effluent obtained from a municipal sewage treatment plant. They conducted the experiment in a cylindrical boro-silicon glass photo-reactor system with an effective volume of 1.1 L containing in the centre an installed NEC black light lamp (T10 20 W) to serve as the UV irradiation source. The filtered secondary effluent mixed with TiO_2 as a sensitizer was pumped into the photo-reactor setup at a hydraulic retention time of 60 min. The aftermath of their experiment achieved a significant reduction in total coliforms and *E. coli* from 3500/100 mL to (59/100 mL) thus, meeting the Hong Kong environmental effluent discharge standards. For the effectiveness of this process, the pH should be at 6.9, the temperature at 21ºC, and the concentration of TiO_2 and dissolved oxygen should be at the optimal values of 2 g/L and 4-5 mg/L respectively. Even though this method proved effective in reducing total coliforms and *E. coli* (Li et al., 1996), knowledge on the physico-chemical parameters (BOD, COD, SS, and Turbidity) of the secondary effluent used were not provided to know what was left after filtration though 1 µm filter papers. Unlike in the studies conducted by Jensen et al. (2013), the effluent filtered through 60 µm used for the UV-C treatment achieved 4 size orders reduction of *enterococci* which could be due to the differences in the secondary effluents qualities.

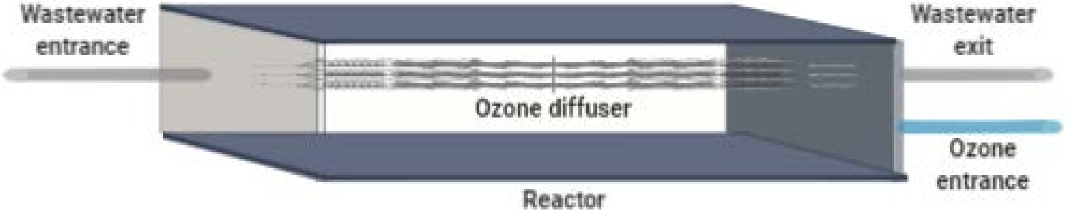


Fig. 7. Schematics of an EB reactor (1) screws (2) upper frame (3) lower frame (4) reactor (5) wastewater entrance (6) wastewater exit (7) ozone entrance (8) ozone diffuser (adapted from Emami-Meibodi et al., 2016)

A nitrogen, N-doped TiO_2 (NDT) Photocatalysis as an alternative option for urban wastewater disinfection was examined by Rizzo et al. (2014) on a wastewater with these characteristics; pH 7.9, BOD_5 10.0 mg/L, COD 23.3 mg/L, TSS 32.5 mg/L, conductivity 1,105 µS/cm, *E. coli* strain 10^7 CFU/100 mL, and redox potential 63.6 mV. According to Rizzo et al. (2014), the photocatalytic disinfection of the wastewater at 0.2 g/L NDT dose for 10 min of irradiation with 250 W lamp resulted in higher inactivation of antibiotic-resistant *E. coli* strain at an inactivation rate of 8.5 x 10^5 CFU/100mL/min; a complete inactivation could be achieved within 60 min of irradiation. This result showed a better performance in terms of pathogenic *E. coli* reduction compare to that performed by Li et al. (1996) using TiO_2 sensitised photo-oxidation for the similar exposure time of 60 min. However, the exact concentration of TiO_2 used in Rizzo et al. (2014) studies was not stated whilst Li et al. (1996) used an optimum value of 2 g/L NDT.

A combined disinfection process (solar/UV photocatalytic ozonation) was also employed by Mecha et al. (2017) to eliminate wastewater pathogens specifically *Salmonella spp., E. coli, V. cholerae* and *Shigella spp*. found in a synthetic municipal secondary effluent. They found out using synergic indices that both the combined processes, UV or solar photocatalytic ozonation were more effective in pathogens inactivation as compared to using the individual method (photocatalysis or ozonation). The results from the photocatalytic disinfection obtained by Rizzo et al. (2014) could not be directly compared to that obtained by Mecha et al. (2017) due to the variation in the reactors configuration or operating conditions, initial microbial concentrations, contact time and general wastewater characteristics (Mecha et al., 2017).

An ecologically and friendly method of municipal wastewater disinfection was applied to achieve a pathogen-safe effluent discharge. The radiation from the sun is sequestered either from the normal global irradiation source or form source concentrated by mirrors into the wastewater through the help of a catalytic photosensitizer dissolved; and the oxidative species (O_2, H_2O_2, O_2^-, OH etc.) produced by the sunlight in the wastewater was used to destroy the microorganisms and cause the oxidation of organic matter. This method is reliably simple and cost-effective with no release of toxic products (Acher et al., 1997).

Acher et al. (1997) performed three comparable separate experiments to disinfect municipal wastewater using the direct normal solar energy or concentrated solar irradiation and artificial UV radiation as sources of disinfectants. An activated sludge treated effluent was obtained for the solar-photooxidation disinfection experiment and exposed to solar photon flux density greater than 750 $\mu Em^{-2} s^{-1}$ or 0.280 kW/m^2. After a disinfection time of about 35 min, the reduction in the microbial population was between 4-5 size orders of magnitude. This result was higher than that obtained by Acher et al. (1994) in the microbial disinfection using sunlight on domestic effluent meant for reuse for crop production. The sunlight intensities of 1600 ± 900 $\mu Em^{-2}s^{-1}$ resulted in the following microbial log reductions; faecal coli (3.12 ± 0.2), coliforms (3.2 ± 0.3), faecal *streptococci* (3.9 ± 0.3) and *poliovirus* (1.9 ± 0.25) (Acher et al., 1994). The difference in the results may be due to the concentration difference in methylene blue used in both studies. The dye-sensitizer (methylene blue) which helps in fast absorption of the solar energy to enhance the photochemical oxidation of the process can be removed from the final disinfected effluent by passing through a simple fast sand filtration unit (Acher et al., 1997). Conversely, as reported by Acher et al. (1997), a technically concentrated sunlight (by concave mirrors) of about 150 kW of solar radiation was focused for 3 s on similar effluent and resulted in about five orders of magnitude in microorganisms (*E. coli* and *poliovirus*) reduction. The third experiment performed by Acher et al. (1997) was to disinfect a high-turbid wastewater (up to 30 NTU) using a newly built multi-tubular-photoreactor (MTP) capable of concentrating the emitted UV light from a low-pressure Hg lamp onto a transparent quartz channel within which the water flows at 5 m^3/h (Acher et al. 1997). Eight of the UV lamp (45 W each) surrounded the central water channel within which the turbid effluent (8 to 30 NTU) flows. The outcome of the results proved more effective compared to that obtained by Li et al. (1996) which reduced *E. coli* and total coliform from 3500 to 59/100 mL wastewater (98% reduction); this could be attributed to the high concentrated UV dose used in the MTP experiment.

Glady-Croue et al. (2018) investigated the disinfection effect of artificial solar radiation in inactivating the antibiotic-resistant bacteria (ARB) and total culturable heterotrophic bacteria present in secondary effluent. It was found that most of the ARB and the total heterotrophic bacteria were inactivated by the solar radiation; with an increased in the relative abundance of certain ARB in the medium. A 60 min of solar irradiation resulted in microbial reduction from $1.1 \times 10^4 \pm 2.7 \times 10^2$ CFU/mL to 12.5 ± 2 CFU/mL, equivalent to 2.94-log reduction. These results were close to that obtained by Acher et al. (1994) with differences in microbial pathogens.

Nasser et al. (2012) evaluated the removal and inactivation of *Giardia* from raw wastewater using the various treatment and disinfection technologies such as stabilisation ponds, activated sludge process, UV disinfection, high-rate sand filtration and ultrafiltration. A *Giardia* reduction of 1-2 orders of magnitude was achieved by the activated sludge whilst a 100% removal of the *Giardia cysts* with high retention time was achieved by the stabilisation ponds using secondary effluent. The highest removal of *Giardia cysts* (>2.4-log) was achieved by ultrafiltration (Nasser et al., 2012). Liberti and Notarnicola (1999) reported high effectiveness of ozone and UV disinfection of *Giardia cysts* which is quite contrary or different to the result of Nasser et al. (2012) for UV specifically. The differences may be due to the varying concentration of the parasites and the methods of analyses. The removal of cysts by filtration process is not always effective (Payment et al., 2011).

Venieri et al. (2017) examined the inactivation efficiency of *Klebsiella pneumoniae* present in sewage effluent using simulated solar irradiation on the effluent containing metal-doped catalysts (Manganese and Cobalt-doped TiO_2 catalysts). About 4 to 6-log reduction of the bacterial population from the initial concentration of 10^7 CFU/mL was achieved using 0.1 wt% Mn and 0.1 wt% Co-doped titania after exposing to about 40 Wh of simulated solar irradiation energy in 30 min (Venieri et al., 2017). A significant reduction of 97% in 30 min was achieved when an NDT photocatalyst for the inactivation of an antibiotic-resistant *E. coli* strain was investigated by Ata et al. (2017). These results were in agreement with the result obtained by Li et al. (1996) where only TiO_2 (un-doped) titania was used to reduce total coliforms and *E. coli* from 3,500/100 mL to (59/100 mL) under artificial UV irradiation of 20 W capacity. However, since the energy sources and intensities, and the microorganisms considered in the studies conducted by Venieri et al. (2017) and Li et al. (1996) are completely different, direct comparison of the two methods is, however, a difficult task (Acher et al., 1997). However, the application of photocatalytic disinfection method has not been thoroughly established in wastewater treatment processes (Gamage and Zhang, 2010). Rincon and Pulgarin (2004) reported that *enterococcus* species found in wastewater plant were observed to be less sensitive to photocatalytic disinfection treatment than coliforms and other gram-negative bacteria.

Nogueira et al. (2016) investigated the physical-chemical disinfection processes that can be used to effectively reduce *Legionella pneumophila* found in municipal wastewater prior to discharge into the river Waster. From their studies, they concluded that the physical-chemical disinfection methods such as chlorine dioxide (0.2-2.4 mg/g), ozone (9.8-237 mg/g), silver micro-particles (6.4-73 µg/g), alkalisation (pH 12.0), hydrogen peroxide (122-2,504 mg/g), and ultrasonic treatment were ineffective at reducing the *Legionella* organisms, but UV treatment alone proved effective and reduced *Legionella spp.* by 1.6-3.4-log units from the secondary effluent. The physical treatment tests were conducted only at the activated sludge stage, it may be relevant for Nogueira et al. (2016) to conduct similar experiments for post-secondary treatment to confirm the effectiveness of the physical-chemical disinfection methods. However, hydrogen peroxide with an optimal dose of 2.5 mL/L was effectively used to inactivate total coliforms exponentially by 3-log order of magnitude after 120 min from a secondary effluent of municipal wastewater (Ksibi, 2006). The inactivation of *E. coli* present in a synthetic secondary effluent by ultrasound and mild photo-Fenton treatment were conducted by Giannakis et al. (2015). Secondary effluent containing an initial bacterial population of 10^6 CFU/mL was subjected to the test in which hydrogen peroxide and iron were used as the Fenton reagents. The outcome of the experiment showed that the application of ultrasound with photo-Fenton was effective in disinfecting *E. coli* with about 82.1% reduction. Iron in Fenton reagent plays no major role in bacterial disinfection (Giannakis et al., 2015). A real wastewater effluent sample containing some level of impurities should be used for this experiment to ascertain its disinfection efficiency. An almost similar process, a solar-enhanced AOP (TiO_2 solar-photocatalysis and solar-photo-Fenton) was used by Tsydenova et al. (2015) to simultaneously remove chemical pollutants and inactivate pathogens from treated water and wastewater. The solar-enhanced AOPs; TiO_2-solar-photocatalysis and solar-photo-Fenton were observed to effectively inactivate a higher percentage of pathogens, (3-log *E. coli* in 120 min) and (100% *E. faecalis* in 10 min) with an initial average concentration of 10^6 CFU/mL (Tsydenova et al., 2015).

Rodríguez-Chueca et al. (2014) studied the inactivation of faecal bacteria (*Enterococcus spp.* and *E. coli)* in urban wastewater effluent using Fenton-like processes induced by radiofrequency. A higher inactivation of 3.55-log *E. coli* was achieved than obtained for *enterococcus* after 10 min of treatment using a combination of F^{3+}/H_2O_2/radiofrequency; the differences in the inactivation of the two species was due to the strong resistant of *enterococcus* than *E. coli* (Rodríguez-Chueca et al., 2014).

Khan et al. (2019) discussed the treatment options for hospital wastewater treatment as the effluents from hospitals are the breeding grounds for pathogenic microorganisms. Several treatment options are documented such as ozonation, filtration and chlorination. However, single stage removal methods have several practical complications. The authors recommended a combination of MBR and Fenton's technologies for effective treatment of hospital wastewater.

The disinfection of *E. coli* using a combination of ozone and hydrodynamic cavitation generated using a liquid whistle reactor (LWR) was analysed by Chand et al. (2007). A simulated effluent containing about 10^8-10^9 CFU/mL of *E. coli* was subjected to the hydrodynamic cavitation and ozone treatment, which resulted in nearly 75% reduction in approximately 3 h of treatment (Chand et al., 2007).

Nonetheless, the inactivation of *Ascaris lumbricoides* eggs in domestic effluent was investigated by de Souza et al. (2011) using gamma-radiation from ^{60}Co as the source. The treated effluent originally infested with about 1,000 non-embryonated *Ascaris lumbricoides* eggs was reported to effectively disinfect *A. lumbricoides* contaminated effluent in high concentration and low concentration using radiation doses of 5 kGy and 3.5 kGy respectively (de Souza et al., 2011). The effect of ^{60}Co-gamma irradiation to disinfect indicator bacteria (*Enterococcus spp.*) in treated municipal wastewater was investigated by Emre et al. (2011). The lethal irradiation doses of at least 5,000 Gy and 900 Gy and 1,500 Gy were effectively used to inactivate total coliforms, *Salmonella spp., Enterococcus spp.* and Faecal *streptococci* at 99.99% inactivation values (Emre et al., 2011).

Verbyla and Mihelcic (2015) conducted a reviewed on the removal efficacy of viruses from 70 different wastewater treatment ponds across the globe and concluded that a weak to moderate correlation existed between the log removal rate of viruses and the hydraulic retention time. For every 14.5-20.9 days retention time, only a 1-log reduction of viruses was achieved (Verbyla and Mihelcic, 2015).

4. Selection of suitable wastewater disinfection processes

Various wastewater disinfection processes such as AOPs disinfection and combined disinfection, singly applied disinfection and other disinfection processes have successfully been employed for pathogen control (Table 3). These are known as conventional or advanced disinfection and other disinfection processes (Collivignarelli et al., 2018). Most of the studies were conducted in developed countries. About 70% of the conducted studies attained more than 3-log reduction of pathogen indicators such as *E. coli* and most of the combined disinfection processes generally proved to be more effective than the singly applied methods, for instance, ozone alone reduced *E. coli* by 4.6-log, and 5-log reduction when combined with peroxide (Malvestiti and Dantas, 2018). The sequential or simultaneous application of two or more disinfectants (known as interactive disinfection) is more effective than a single applied disinfectant method (Tchobanoglous et al., 2003; USEPA, 1999). The disinfection performance of UV or ozone can be enhanced by combining with other disinfection processes such as peracetic acid. Hence, the combined effect of disinfection processes such as combining ozonation with photocatalysis can help to improve disinfection performance (Mecha et al., 2017; USEPA, 1999). The total coliforms and *E. coli* were the dominants microbial indicator organisms used by most researchers in their various disinfection experiments.

Most of the single applied disinfection methods can also well reduce or inactivate *E. coli* and total coliforms as is shown in Table 4. *Legionella pneumophila, E. coli, Enterococci,* reoviruses and enteric viruses were best removed using the single UV disinfection method. In addition to removing *E. coli* and total coliforms, ozonation was also suitable for *Enterobacter, Klebsiella, Serratia, and Citrobacter.* Solar irradiation was also suitable in inactivating Poliovirus and total coliforms whilst Cobalt-60 gamma irradiation was suitable for faecal *streptococci* and *Salmonella spp.*

The log reduction range of various wastewater pathogens is provided in Table 5. It showed that *E. coli* can be significantly reduced by UV, ozonation, chlorination and membrane filtration. The log reduction of *E. coli* (2-4-log) using UV irradiation agreed with that obtained by Stampi et al. (2001). This showed that UV irradiation was effective in reducing *E. coli.*

Also, considering the combination of the disinfection processes in Table 6, just like the single disinfection processes, *E. coli* and total coliforms can generally be removed by most of the disinfection processes. The antibiotic-resistant *E. coli* was tested to be effectively inactivated by UV followed by chlorination processes. The combined effect of SBBGR and peracetic acid or UV was good at reducing *E. coli* and coliforms in up to five order magnitude. CWs/UV and Solar/UV photocatalytic ozonation were found to be suitable for four sets of microorganisms: for CWs/UV; *E. coli, C. perfringens* spores, *enterococci* and total coliforms, and Solar/UV photocatalytic ozonation; *V. cholerae, Shigella spp., E. coli* and *Salmonella spp.*

The results tabulated in Tables 3, 4, and 6 are essentially important considerations in selecting a suitable disinfection process. As different wastewaters may contain various microbial pathogens, which generally response differently to the various disinfection processes, a comprehensive assessment ought to be conducted prior to selection. The use of UV and chlorination or their combinations were proven to effectively reduce *E. coli* up to a 6-log in wastewater (Aslan et al., 2018; NWQMS, 2006). Peracetic acid was considered as a viable alternative to chlorine and had been successfully used to inactivate *Enterococci,* total coliforms and *E. coli* up to a 4-log from sewage effluent of a full-scale treatment plant at a minimal dose of 2 mg/L (Stampi et al., 2001). Various disinfection processes possess some advantages and disadvantages over one another that need to be considered. Chlorination was reported to be more effective than peracetic acid in terms of the wide range of microbial inactivation (Stampi et al., 2002), but residual chlorine concentration can be very toxic to aquatic species or humans (Verbyla and Mihelcic, 2015). Ozone can inactivate bacteria, viruses and some protozoa in a short time however, it is relatively complex and of high cost (Collivignarelli et al., 2018; WHO, 2006).

Table 3. Various disinfection processes for domestic wastewater discharge

WW Disinfection Technologies	*Study Scales*	*Effectiveness*	*Organisms Log Reduction*	*Effluent types*	*References*
AOPs and Combined Disinfection Systems					
Ozone and Peroxide	Lab	*E. coli,* total coliforms	~5.0		

WW Disinfection Technologies	***Study Scales***	***Effectiveness***	***Organisms Log Reduction***	***Effluent types***	***References***
UV and Peroxide		*E. coli*, total coliforms	~5.0	Secondary effluent	Malvestiti and Dantas (2018)
Ozone		*E. coli*, total coliforms	~4.6		
UV + Chlorination	Full	Antibiotic-resistant *E. coli*	5.2 + 1.1	Plant effluent	Aslan et al. (2018)
Microwave and UV irradiation	Lab	Total coliforms	5.0	Municipal secondary effluent	(Zhang et al., 2017)
		Total bacterial count	3.0		
UV + Biofiltration + UV	Full	Total coliforms	<1.0 + <1.0 + 4.0	Domestic wastewater	Bilotta and Daniel (2010)
		E. coli	1.0 + 2.0 + 5.0		
Solar photocatalytic ozonation	Pilot	*Salmonella spp., E. coli, V. cholerae* and *Shigella spp.*	1.0-2.3	Synthetic and secondary effluent	Mecha et al. (2017)
UV photocatalytic ozonation					
Ozone and hydrodynamic cavitation	Lab	*E. coli*	< 2.0	Simulated effluent	Chand et al. (2007)
Single Applied Disinfection Processes					
UV	Full	*E. coli*	5.2	Plant effluent	Aslan et al. (2018)
UV	Pilot	*Enterococci*	> 4.0	Sewage sample	Jensen et al. (2013)
UV	Full	Total infectious viruses	1.6	Wastewater effluent	Qiu et al. (2018)
		Reovirus	1.49		
UV	Full	*Legionella pneumophila*	1.6-3.4	Secondary effluent	Nogueira et al. (2016)
UV/PAA	Pilot	Total coliforms	≥ 5.0	Clarified secondary feed	Liberti and Notarnicola (1999)
Ozone		Total coliforms	≤ 4.0		
Ozone	Lab	*E. coli, Enterobacter, Klebsiella, Serratia, Citrobacter* and total coliforms	> 2.0	Secondary effluent	Verma et al. (2016), Luczkiewicz et al. (2011)
UV	Pilot	*Enterococci*	> 4.0	Sewage sample	Jensen et al. (2013)
PAA		Coliforms and Enterococci	2.0-3.0		
		E. coli	> 6.0		
PAA	Full	*Enterococci*	4.0	Sewage effluent	Stampi et al. (2001)
		Total coliforms and *E. coli*	5.0		
Ferrate VI ion	-	*E. coli*, total coliforms	4.0	Wastewater	Jiang (2001, 2014)
Hydrogen peroxide	Full	Total faecal coliforms	3.0	Secondary effluent	Ksibi (2006)
Tin oxide anode	Bench/lab	Total coliforms	5.0	-	Loge et al. (2006)
EB irradiation	Pilot	Coliforms	> 90%	Plant effluent	Emami-Meibodi et al. (2016)
Photo-oxidation (TiO_2)	Pilot	*E. coli*, total coliforms	99.8%	Secondary effluent	Li et al. (1996)
Photo-oxidation (N-TiO_2)	Lab	Antibiotic resistant *E. coli* strain	5.0	Wastewater effluent	Rizzo et al. (2014)
Solar irradiation (Mn/Co-TiO_2)	Lab	*Klebsiella pneumoniae*	4.0-6.0	Sewage effluent	Venieri et al. (2017)
Natural sunlight	Lab/pilot	*E. coli*, poliovirus	4.0-5.0	Treated effluent	Acher et al. (1997)
Concentrated sunlight			5.0		
Multi-tubular photoreactor		*E. coli*	8.0	Treated effluent (turbid)	
		Enterococci, poliovirus	5.0		
Micro/ultrafiltration	Pilot	Faecal coliforms	> 2.0	Secondary effluent	Luczkiewicz et al. (2011)
Ultrafiltration	-	*Giardia cysts*	> 2.4	Secondary effluent	Nasser et al. (2012)
^{60}Co-gamma irradiation	Lab	*Salmonella spp., Enterococcus spp.*	4.0		Emre et al. (2011)

WW Disinfection Technologies	***Study Scales***	***Effectiveness***	***Organisms Log Reduction***	***Effluent types***	***References***
		Total coliforms, Faecal *streptococci*	4.0		
Other Disinfection Processes					
SBBGR + UV	Lab	Total coliforms *E. coli*	2.5 + 3.0 2.5 + 3.0	Domestic wastewater	De Sanctis et al. (2016)
SBBGR + Peracetic acid		Total coliforms	2.5 + 3.0		
		E. coli	2.5 + ~3.0		
SBBGR + Sand filtration/filtration	Pilot	*C. perfringens*	1.1 + 2.7	Domestic wastewater	De Sanctis et al. (2017)
		E. coli	3.2 + 4.2		
Sand Filtration + UV	Full	Faecal coliforms	0.8 + 2.9	Wastewater effluent	George et al. (2002)
Ultrasound and ClO_2	Lab	Faecal coliform	4.4	Secondary effluent	Zhou et al. (2016)
Ultrasound and Fenton reagents	Lab	*E. coli*	82.1%	Synthetic secondary effluent	Giannakis et al. (2015)
Radiofrequency and Fenton reagents	Lab	*E. coli*	3.6	Wastewater effluent	Rodríguez-Chueca et al. (2014)
HSF + NaClO	Pilot	*E. coli*	2.6-2.7	Secondary effluent	Verlicchi et al. (2009)
CWs + UV	Full	*E. coli*	1.2 + < 2.8	Treated secondary effluent	Russo et al. (2019)
		Total coliforms	1.3 + 3.1		
		Enterococci	1.8 + 1.8		
		C. perfringens spores	1.3 + <1		
CWs + Sand filtration	Pilot	*Esherichia coli,* total coliforms, *Enterococci*	2.5 + 1.1	Primary domestic wastewater	Kaliakatsos et al. (2019)
		Adenoviruses and Enteroviruses	2.5-3.4		

Note: *All units are in logarithmic reduction unless otherwise stated.*

Table 5. Indicative log reduction of enteric pathogens and indicator organisms

Treatment/ Disinfection	***E. coli***	***Bacterial Pathogens (including Campylobacter)***	***Viruses (including adenoviruses, rotaviruses and enteroviruses)***	***Giardia***	***Cryptosporidium***	***C. perfringens***	***Helminths***
UV irradiation	2.0 – >4.0	2.0 – >4.0	Adenovirus >1, enterovirus, hepatitis A >3	>3.0	>3.0	N/A	N/A
Ozonation	2.0 – 6.0	2.0 – 4.0	3.0 – 4.0	N/A	N/A	0.0 – 0.5	N/A
Chlorination	2.0 – 6.0	2.0 – 6.0	1.0 – 3.0	0.5 – 1.5	0 – 0.5	1.0 – 2.0	0.0 – 1.0
Membrane filtration	3.5 – >6.0	3.5 – >6.0	2.5 – >6.0	>6.0	>6.0	>6.0	>6.0
Wetlands surface flow	1.5– 1.5	1.0	N/A	0.5 – 1.5	0.5 – 1.0	1.5	0.0 – 2.0
Wetlands subsurface flow	0.5 – 3.0	1.0 – 3.0	N/A	1.5 – 2.0	0.5 – 1.0	1.0 – 3.0	N/A

Source: NWQMS, 2006.
Note: *N/A - not available.*

5. Conclusions

A systematic literature review was undertaken in this work, in which several disinfection processes were identified, to describe the suitable disinfection processes that can be applied in wastewater treatment plant prior to effluent discharges as wastewater may contain various microbial pathogens which respond distinctively to different disinfection methods. The UV irradiation system, among other disinfection methods, was the most employed in the disinfection studies conducted by most of the researchers under this review.

Combined disinfection processes, in general, proved to be more effective than the singly applied methods.

Table 6. Comparison of the effective inactivation of various microbial pathogens disinfection processes (combined methods)

Microorganisms	***Disinfection Processes (AOPs and Combined Disinfection Methods)***										
	UV/ Peroxide	***Ozone/ Peroxide***	***UV/ Chlorination***	***Microwave/UV Irradiation***	***UV/ Biofiltration/UV***	***Solar/UV Photocatalytic Ozonation***	***Ozone/ Hydrodynamic Cavitation***	***CWs/ UV***	***CWs/Sand Filtration***	***SBBGR + Peracetic Acid***	***SBBGR/UV***
E. coli	√	√			√	√	√	√	√	√	√
Antibiotic-resistant *E. coli*			√								
Total coliforms	√	√		√	√			√	√	√	√
V. cholerae						√					
Shigella spp.						√					
Enterococci								√	√		
Adenoviruses									√		
C. parvum											
G. lamblia											
Enteric viruses									√		
Total bacteria count											
Salmonella spp.						√					
C. perfringens spores								√			

Full-scale studies are more likely to represent the actual performance of the disinfection processes. Therefore, the pilot plant studies of some of the disinfection processes such as ozone, solar disinfection, ozone/peroxide and others that were successfully done in laboratory scales should be conducted/applied in full-scale to ascertain their effectiveness and actual performances.

Furthermore, the disinfection studies should be conducted on wastewater treatment plants in developing countries, especially using a UV irradiation system. With a better understanding of the pathogen control processes, this research will help the industry/government policymakers in devising methods to restore the contaminated water resources.

References

Acher A., Fischer E., Turnheim R., Manor Y., (1997), Ecologically friendly wastewater disinfection techniques, *Water Research*, **31**, 1398-1404.

Acher A.J., Fischer E., Manor Y., (1994), Sunlight disinfection of domestic effluents for agricultural use, *Water Research*, **28**, 1153-1160.

Afzal M.S., Ashraf A., Nabeel M., (2018), Characterization of industrial effluents and groundwater of Hattar industrial estate, Haripur, *Advances in Agriculture and Environmental Science*, **1**, 70-77.

Ajonina C., Buzie C., Rubiandini R.H., Otterpohl R., (2015), Microbial pathogens in wastewater treatment plants (WWTP) in Hamburg, *Journal of Toxicology and Environmental Health - Part A: Current Issues*, **78**, 381-387.

Ashraf A., Chen X., Ramamurthy R., (2020). Modelling heavy metals contamination in groundwater of Southern Punjab, Pakistan, *International Journal of Environmental Science and Technology*, http://doi.org10.1007/s13762-020-02965-w.

Aslan A., Cole Z., Bhattacharya A., Oyibo O., (2018), Presence of antibiotic-resistant *Escherichia coli* in wastewater treatment plant effluents utilized as water reuse for irrigation, *Water*, **10**, 805, http://doi.org/10.3390/w10060805.

Ata R., Sacco O., Vaiano V., Rizzo L., Tore G.Y., Sannino D., (2017), Visible light active N-doped TiO_2 immobilized on polystyrene as efficient system for wastewater treatment, *Journal of Photochemistry and Photobiology A: Chemistry*, **348**, 255-262.

Bilotta P., Daniel L.A., (2010), Advanced process of microbiological control of wastewater in combined system of disinfection with UV radiation, *Water Science and Technology*, **61**, 2469-2475.

Bonetta S., Pignata C., Lorenzi E., De Ceglia M., Meucci L., Bonetta S., Gilli G., Carraro E., (2017), Peracetic acid (PAA) disinfection: Inactivation of microbial indicators and pathogenic bacteria in a municipal wastewater plant, *Water*, **9**, 1-10.

Bozorg-Haddad O., Abutalebi M., Chu X., Loáiciga H.A., (2020), Assessment of potential of intraregional conflicts by developing a transferability index for inter-basin water transfers, and their impacts on the water resources, *Environmental Monitoring and Assessment*, **192**, 40, http://doi.org/10.1007/s10661-019-8011-1.

Bustos Y., Vaca M., López R., Bandala E., Torres L., Rojas-Valencia N., (2014), Disinfection of primary municipal wastewater effluents using continuous UV and ozone treatment, *Journal of Water Resource and Protection*, **6**, 16-21.

Campo N., De Flora C., Maffettone R., Manoli K., Sarathy S., Santoro D., Gonzalez-Olmos R., Auset M., (2020), Inactivation kinetics of antibiotic resistant Escherichia coli in secondary wastewater effluents by peracetic and performic acids, *Water Research*, **169**, 115227, https://doi.org/10.1016/j.watres.2019.115227.

Cesaro A., Naddeo V., Belgiorno V., Vincenzo N.A.C., (2013), Wastewater treatment by a combination of advanced oxidation processes and conventional biological systems, *Journal of Bioremediation and Biodegradation*, **4**, 208, http://doi.org/10.4172/2155-6199.1000208.

Chand R., Bremner D.H., Namkung K.C., Collier P.J., Gogate P.R., (2007), Water disinfection using the novel approach of ozone and a liquid whistle reactor, *Biochemical Engineering Journal*, **35**, 357-364.

Cheng G., Li Z., Sun L., Li Y., Fu J., (2020), Application of microwave/electrodeless discharge ultraviolet/ozone sterilization technology in water reclamation, *Process Safety and Environmental Protection*, **138**, 148-156

Collivignarelli M.C., Abbà A., Benigna I., Sorlini S., Torretta V., (2018), Overview of the main disinfection processes for wastewater and drinking water treatment plants, *Sustainability*, **10**, 86, https://doi.org/10.3390/su10010086.

Contreras S., Pascual E., Esplugas S., Gim J., (2002), Comparison of different advanced oxidation processes for phenol degradation, *Water Research*, **36**, 1034-1042.

Edokpayi J.N., Odiyo J.O., Durowoju O.S., (2017), *Impact of Wastewater on Surface Water Quality in Developing Countries: A Case Study of South Africa*, In: *Water Quality*, Tutu H. (Ed.), IntechOpen, http://doi.org/10.5772/66561, 401-416.

Emami-Meibodi M., Parsaeian M.R., Amraei R., Banaei M., Anvari F., Tahami S.M.R., Vakhshoor B., Mehdizadeh A., Fallah Nejad N., Shirmardi S.P., Mostafavi S.J., Mousavi S.M.J., (2016), An experimental investigation of wastewater treatment using electron beam irradiation, *Radiation Physics and Chemistry*, **125**, 82-87.

Emre Z., Altay Çapin G., Canpolat S., Mert H., (2011), Inactivation of indicator bacteria in treated municipal wastewater and biosolids by gamma irradiation, *Ankara Üniversitesi Veteriner Fakültesi Dergisi*, **58**, 55-59.

Gamage J., Zhang Z., (2010), Applications of photocatalytic disinfection, *International Journal of Photoenergy*, 764870, https://doi.org/10.1155/2010/764870.

George I., Servais P., Crop P., (2002), Faecal coliforms removal in wastewater treatment plants studied by plate counts and enzymatic methods, *Water Research*, **36**, 2607-2617.

Ghernaout D., Naceur M.W., (2011), Ferrate (VI): In situ generation and water treatment – A review, *Desalination and Water Treatment*, **30**, 319-332.

Giannakis S., Papoutsakis S., Darakas E., Escalas-Cañellas A., Pétrier C., Pulgarin C., (2015), Ultrasound enhancement of near-neutral photo-Fenton for effective *E. coli* inactivation in wastewater, *Ultrasonics Sonochemistry*, **22**, 515-26.

Glady-Croue J., Niu X.Z., Ramsay J.P., Watkin E., Murphy R.J.T., Croue J.P., (2018), Survival of antibiotic resistant bacteria following artificial solar radiation of secondary wastewater effluent, *Science of the Total Environment*, **626**, 1005-1011.

Godfree A., (2003), *Health Constraints on the Agricultural Recycling of Wastewater Sludge*s, In: *The Handbook of Water and Wastewater Microbiology*, Mara D., Horan N. (Eds.), Academic Press, 281-298.

Hassaballah A.H., Bhatt T., Nyitrai J., Dai N., Sassoubre L., (2020), Inactivation of *E. coli*, *Enterococcus spp.*, somatic coliphage, and *Cryptosporidium parvum* in wastewater by peracetic acid (PAA), sodium hypochlorite, and combined PAA-ultraviolet disinfection, *Environmental Science: Water Research and Technology*, **6**, 197-209.

Hijnen W.A.M., Beerendonk E.F., Medema G.J., (2006), Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: A review, *Water Research*, **40**, 3-22.

Hello A.N., Jaeel A.J., (2014), Environmental impact assessment of domestic effluents on water quality of Tigris River discharged from Wasit Thermal Power Plant, *Thi-Qar University Journal for Engineering Sciences*, **5**, 15-31.

Ibrahim S., El-Liethy M.A., Abia A.L.K., Abdel-Gabbar M., Al Zanaty A.M., Kamel M.M., (2020), Design of a bioaugmented multistage biofilter for accelerated municipal wastewater treatment and deactivation of pathogenic microorganisms, *Science of the Total Environment*, **703**, 134786, https://doi.org/10.1016/j.scitotenv.2019.134786.

Jensen P.E., Gunnarsdottir R., Andersen H.R., Martinsen G., Nicolajsen E.S., Davidsen S., Toke J., (2013), Levels and treatment options for enteric and antibiotic-resistant bacteria in sewage from Sisimiut, Greenland, *ISCORD 2013: Planning for Sustainable Cold Regions*, 779-790.

Jiang J.Q., (2014), Advances in the development and application of ferrate(VI) for water and wastewater treatment, *Journal of Chemical Technology and Biotechnology*, **89**, 165-177.

Jonnalagadda S.B., Mhere G., (2001), Water quality of the odzi river in the Eastern Highlands of Zimbabwe, *Water Research*, **35**, 2371-2376.

Kaliakatsos A., Kalogerakis N., Manios T., Venieri D., (2019), Efficiency of two constructed wetland systems for wastewater treatment: Removal of bacterial indicators and enteric viruses, *Journal of Chemical Technology and Biotechnology*, **94**, 2123-2130.

Khan N.A., Ahmed S., Vambol S., Vambol V., Farooqi I.H., (2019), Field hospital wastewater treatment scenario, *Ecological Questions*, **30**, 57-69.

Khan N.A., Khan K.A., Islam M., (2012), *Water and Wastewater Treatment using Nano-Technology*, In: *Chemistry of Phytopotentials: Health, Energy and Environmental Perspectives*, Springer, 315-318.

Khan N.A., Khan S.U., Ahmed S., Farooqi I.H., Yousefi M., Mohammadi A.A., Changani F., (2020), Recent trends in disposal and treatment technologies of emerging-pollutants-A critical review, *TrAC Trends in Analytical Chemistry*, **122**, 115744, https://doi.org/10.1016/j.trac.2019.115744.

Kitis M., (2004), Disinfection of wastewater with peracetic acid: A review, *Environment International*, **30**, 47-55.

Ksibi M., (2006), Chemical oxidation with hydrogen peroxide for domestic wastewater treatment, *Chemical Engineering Journal*, **119**, 161-165.

Lane S., Lloyd D., (2002), Current trends in research into the waterborne parasite Giardia, *Critical Reviews in Microbiology*, **28**, 123-147.

LeChevallier M.W., Au K.-K., (2004), *Water Treatment And Pathogen Control: Process Efficiency in Achieving Safe Drinking-Water*, IWA Publishing, World Health Organization.

Li X.Z., Zhang M., Chua H., (1996), Disinfection of municipal wastewater by sensitized photooxidation, *Water Science and Technology*, **33**, 111-118.

Liberti L., Notarnicola M., (1999), Advanced treatment and disinfection for municipal wastewater reuse in agriculture, *Water Science and Technology*, **40**, 235-245.

Loge F.J., Inouye T., Watts R.J., (2006), Disinfection of secondary effluents using tin oxide anodes, *Water Environment Research*, **78**, 41-48.

De Luca G., Sacchetti R., Zanetti F., Leoni E., (2008), Comparative study on the efficiency of peracetic acid and chlorine dioxide at low doses in the disinfection of urban wastewaters, *Annals of Agricultural and Environmental Medicine*, **15**, 217-224.

Luczkiewicz A., Jankowska K., Bray R., Kulbat E., Quant B., Sokolowska A., Olanczuk-Neyman K., (2011), Antimicrobial resistance of faecal indicators in disinfected wastewater, *Water Science and Technology*, **64**, 2352-2361.

Luukkonen T., Teeriniemi J., Prokkola H., Rämö J., Lassi U., (2014), Chemical aspects of peracetic acid based wastewater disinfection, *Water SA*, **40**, 73-80.

Ma S., Kim K., Chun S., Moon S.Y., Hong Y., (2020), Plasma-assisted advanced oxidation process by a multi-hole dielectric barrier discharge in water and its application to wastewater treatment, *Chemosphere*, **243**, 125377, https://doi.org/10.1016/j.chemosphere.2019.125377.

Malvestiti J.A., Dantas R.F., (2018), Disinfection of secondary effluents by O_3, O_3/H_2O_2 and UV/H_2O_2: Influence of carbonate, nitrate, industrial contaminants and regrowth, *Journal of Environmental Chemical Engineering*, **6**, 560-567.

Mecha A.C., Onyango M.S., Ochieng A., Momba M.N.B., (2017), Evaluation of synergy and bacterial regrowth in photocatalytic ozonation disinfection of municipal wastewater, *Science of the Total Environment*, **601-602**, 626-635.

Michael H.G., Melvin C.Z., (2005), *Removal, Inactivation, and Destruction of Pathogens*, In: *Wastewater Pathogens*, Gerardi M.H. (Ed.), Wiley-Interscience, 135-140.

Moher D., Liberati A., Tetzlaff J., Altman D.G., (2009), Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement, *Journal of Clinical Epidemiology*, **62**, 1006-1012.

Nahim-Granados S., Rivas-Ibáñez G., Pérez J.A.S., Oller I., Malato S., Polo-López M.I., (2020), Synthetic fresh-cut wastewater disinfection and decontamination by ozonation at pilot scale, *Water Research*, **170**, 115304, https://doi.org/10.1016/j.watres.2019.115304.

Nasser A.M., Vaizel-Ohayon D., Aharoni A., Revhun M., (2012), Prevalence and fate of giardia cysts in wastewater treatment plants, *Journal of Applied Microbiology*, **113**, 477-484.

NWQMS, (2006), National Guidelines for water recycling: Managing health and environmental risks, *National Water Quality Management Strategy – Australian*, On line at: https://www.waterquality.gov.au/guidelines/recycled-water

Nogueira R., Utecht K.U., Exner M., Verstraete W., Rosenwinkel K.H., (2016), Strategies for the reduction of Legionella in biological treatment systems, *Water Science and Technology*, **74**, 816-823.

Okoh A.I., Odjadjare E.E., Igbinosa E.O., Osode A.N., (2007), Wastewater treatment plants as a source of microbial pathogens in receiving watersheds, *African Journal of Biotechnology*, **6**, 2932-2944.

Payment P., Plante R., Cejka P., (2011), Removal of indicator bacteria, human enteric viruses, Giardia cysts, and Cryptosporidium oocysts at a large wastewater primary treatment facility, *Canadian Journal of Microbiology*, **47**, 188-193.

Qasim S.R., (1985), *Wastewater Treatment Plant: Planning, Design and Operational*, Holt, Rinehart, and Winston Publisher, New York.

Qiu Y., Li Q., Lee B.E., Ruecker N.J., Neumann N.F., Ashbolt N.J., Pang X., (2018), UV inactivation of human infectious viruses at two full-scale wastewater treatment plants in Canada, *Water Research*, **147**, 73-81.

Rincon A.G., Pulgarin C., (2004), Bactericidal action of illuminated TiO_2 on pure *Escherichia coli* and natural bacterial consortia: Post-irradiation events in the dark and assessment of the effective disinfection time, *Applied Catalysis B: Environmental*, **49**, 99-112.

Rizzo L., Sannino D., Vaiano V., Sacco O., Scarpa A., Pietrogiacomi D., (2014), Effect of solar simulated N-doped TiO_2 photocatalysis on the inactivation and antibiotic resistance of an *E. coli* strain in biologically treated urban wastewater, *Applied Catalysis B: Environmental*, **144**, 369-378.

Rodríguez-Chueca J., Mediano A., Ormad M.P., Mosteo R., Ovelleiro J.L., (2014), Disinfection of wastewater effluents with the Fenton-like process induced by electromagnetic fields, *Water Research*, **60**, 250-258.

Rosenfeldt E.J., Linden K.G., Canonica S., von Gunten U., (2006), Comparison of the efficiency of ($OH^{\cdot}$) radical formation during ozonation and the advanced oxidation processes O_3/H_2O_2 and UV/H_2O_2, *Water Research*, **40**, 3695-3704.

Russo N., Marzo A., Randazzo C., Caggia C., Toscano A., Cirelli G.L., (2019), Constructed wetlands combined with disinfection systems for removal of urban wastewater contaminants, *Science of the Total Environment*, **656**, 558-566.

De Sanctis M., Del Moro G., Chimienti S., Ritelli P., Levantesi C., Di Iaconi C., (2017), Removal of pollutants and pathogens by a simplified treatment scheme for municipal wastewater reuse in agriculture, *Science of the Total Environment*, **580**, 17-25.

De Sanctis M., Del Moro G., Levantesi C., Luprano M.L., Di Iaconi C., (2016), Integration of an innovative biological treatment with physical or chemical disinfection for wastewater reuse, *Science of the Total Environment*, **543**, 206-213.

De Souza G.S.M.B., Rodrigues L.A., de Oliveira W.J., Chernicharo C.A.L., Guimarães M.P., Massara C.L., Grossi P.A., (2011), Disinfection of domestic effluents by gamma radiation: Effects on the inactivation of Ascaris lumbricoides eggs, *Water Research*, **45**, 5523-5528.

Saxena S.K., Kumar S., Haikerwal A., Maurya V.K., (2020), *Introduction to Water-Associated Infectious Diseases*, In: *Water-Associated Infectious Diseases*, Saxena S.K. (Ed.), Springer, Singapore.

Stampi S., De Luca G., Onorato M., Ambrogiani E., Zanetti F., (2002), Peracetic acid as an alternative wastewater disinfectant to chlorine dioxide, *Journal of Applied Microbiology*, **93**, 725-731.

Stampi S., De Luca G., Zanetti F., (2001), Evaluation of the efficiency of peracetic acid in the disinfection of sewage effluents, *Journal of Applied Microbiology*, **91**, 833-838.

Tchobanoglous G., Burton F.L., Stensel H.D., (2003), *Wastewater Engineering: Treatment and Reuse*, Metcalf & Eddy Inc. McGraw-Hill, Inc, New York, USA, for Environmental Research Information, Cincinnati, Ohio,

Toze R.S.G., (1997), Microbial pathogens in wastewater, *CSIRO Land and Water Technical Report No 1/97*, On line at: http://www.clw.csiro.au/publications/technical97/tr1-97.pdf

Tsydenova O., Batoev V., Batoeva A., (2015), Solar-enhanced advanced oxidation processes for water treatment: Simultaneous removal of pathogens and chemical pollutants, *International Journal of Environmental Research and Public Health*, **12**, 9542-9561.

USEPA, (1999), *Alternative Disinfectants and Oxidants Guidance Manual*, United States Environmental Protection Agency, EPA 815-R-99, On line at: https://nepis.epa.gov/Exe/ZyPDF.cgi/2000229L.PDF?Dockey=2000229L.PDF

UNEP, (2002), *Global Environment Outlook* 3, United Nations Environment Program, On line at: https://www.unep.org/resources/global-environment-outlook-3.

UNEP (2016), *Programme Performance Report*, United Nations Environment Program, https://wedocs.unep.org/bitstream/handle/20.500.11822/16792/PPR_2016.pdf?sequence=1&isAllowed=y

Venieri D., Gounaki I., Bikouvaraki M., Binas V., Zachopoulos A., Kiriakidis G., Mantzavinos D., (2017), Solar photocatalysis as disinfection technique: Inactivation of Klebsiella pneumoniae in sewage and investigation of changes in antibiotic resistance profile, *Journal of Environmental Management*, **195**, 140-147.

Verbyla M.E., Mihelcic J.R., (2015), A review of virus removal in wastewater treatment pond systems, *Water Research*, **71**, 107-124.

Verlicchi P., Galletti A., Masotti L., (2009), A promising practice to reclaim treated wastewater for reuse: Chemical disinfection followed by natural systems, *Desalination*, **247**, 490-508.

Verma K., Gupta D., Gupta A.B., (2016), Optimization of ozone disinfection and its effect on trihalomethanes, *Journal of Environmental Chemical Engineering*, **4**, 3021-3032.

Watts R.J., Wyeth M.S., Finn D.D., Teel A.L., (2008), Optimization of Ti/SnO_2-Sb_2O_5 anode preparation for electrochemical oxidation of organic contaminants in water and wastewater, *Journal of Applied Electrochemistry*, **38**, 31-37.

WHO, (2006), Guidelines for the safe use of wastewater, excreta and greywater: Wastewater use in agriculture, World Health Organisation, On line at: https://www.who.int/water_sanitation_health/wastewater/wwuvol2intro.pdf

Yang Y., Hou Y., Ma M., Zhan A., (2020), Potential pathogen communities in highly polluted river ecosystems: Geographical distribution and environmental influence, *Ambio*, **49**, 197-207.

Zhang Y., Zhang G., Wang P., Wang Q., (2017), Disinfection of municipal secondary effluents with microwave-induced electrodeless ultraviolet irradiation for water reuse, *Journal of Chemical Technology and Biotechnology*, **92**, 1017-1025.

Zhou H., Smith D.W., (2002), Advanced technologies in water and wastewater treatment, *Journal of Environmental Engineering and Science*, **1**, 247-264.

Zhou X., Zhao J., Li Z., Lan J., Li Y., Yang X., Wang D., (2016), Influence of ultrasound enhancement on chlorine dioxide consumption and disinfection by-products formation for secondary effluents disinfection, *Ultrasonics Sonochemistry*, **28**, 376-381.