A methodology for the evaluation of disinfection technologies

M. Kerwick, S. Reddy, D. Holt and A. Chamberlain

ABSTRACT

There are several concerns associated with the use of chlorine for potable water disinfection. These are the resistance of certain pathogens, the formation of toxic disinfection by-products and the adverse effects on aesthetic water quality. Owing to these concerns the water industry is continually reviewing alternative disinfection technologies. A methodology has been devised that will aid the water industry in evaluating the potential of these technologies. The methodology uses seven criteria to evaluate the technologies, these are: inactivation efficiency, disinfection by-product (DBP) formation, toxicity, aesthetic water quality, cost, scalability and residual maintenance. Each criterion is assessed by associated questions in order of importance in accordance with a protocol. The criteria are evaluated using UK water quality regulations as standards. Ultraviolet (UV) disinfection was used as an example to demonstrate the methodology. UV was shown to meet all the criteria apart from the provision of a residual disinfectant. Several other disinfection technologies were evaluated using the methodology. Direct electrochemical disinfection and mixed oxidant generators were identified as having the most potential for replacing chlorination.

Key words | costs, disinfection by-products, disinfection technologies, evaluation methodology, inactivation efficiency, ultraviolet disinfection

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INTRODUCTION

Water has long been associated with the transmission of pathogens relevant to public health. Until the late 19th century typhoid and cholera were responsible for many deaths (Schoenen 2002). The widespread implementation of water treatment strategies including filtration and disinfection throughout the developed world has minimised this threat by reducing the potential for consumption of contaminated water. However, occasional outbreaks of illness such as the protozoan *Cryptosporidium parvum* do still occur (Robertson *et al.* 1994).

At present the main method of drinking water disinfection at the final stage of treatment is chlorination, although others such as ozonation and ultraviolet irradiation are now used more extensively. The discovery more than 25 years ago that the use of chemical disinfectants such as chlorine in drinking water treatment can result in the formation of potentially toxic disinfection by-products (DBPs) has led to public health concerns regarding the safety of drinking water (Singer *et al.* 2002).

As a result of the potential risks associated with the use of chlorine-based disinfection processes and consumer preferences for non-chlorine taste and odours, water providers are continually looking at alternative methods of disinfection. Several alternatives to chlorination have been investigated, these include treatment with: ozone, hydrogen peroxide, iodine species, bromine species, permanganate, ionising radiation, silver, ferrate and UV (Geldrich 1996), copper (Pyle *et al.* 1992), titanium photocatalysis (Matsunaga & Okochi 1995), photodynamic disinfection (Gerba *et al.* 1977), high voltage pulsed electric fields (PEF) (Wouters *et al.* 1999) and ultrasonication (Hua & Tompson 2000). While some are used in water treatment for other purposes, for example

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ozone for pesticide removal, and also contribute to disinfection, they have not replaced chlorine owing to either their cost at an effective dose, or lack of residual for protecting the quality of water in the distribution network.

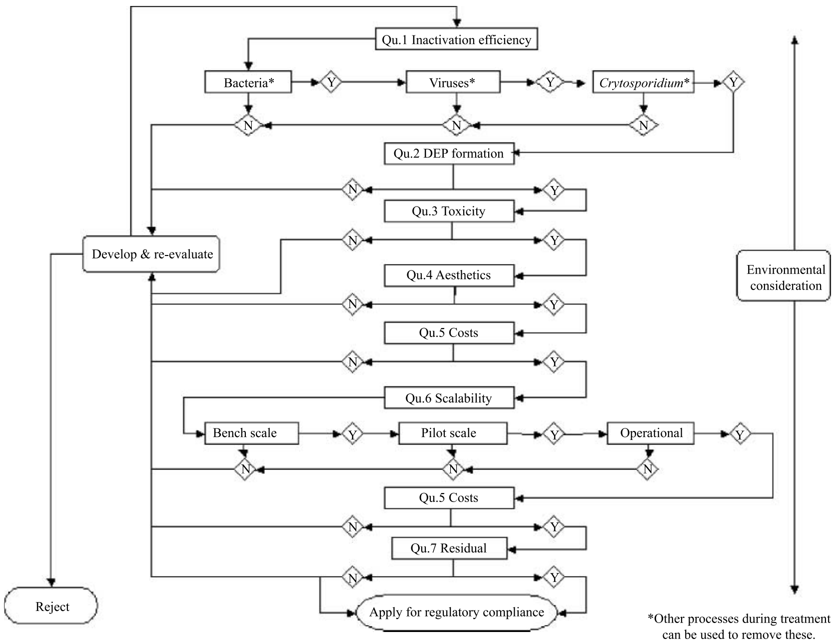
The evaluation of these methods as alternatives to chlorine for drinking water disinfection is an important process for water companies. For a method to replace chlorination it must reach the required standards for a number of criteria. The aim of this paper is to introduce a methodology that is designed to guide the assessor through this evaluation process.

Methodology

A methodology has been devised to aid the evaluation of disinfection technologies at the final disinfection stage and is presented as a flow diagram (Figure 1).

The methodology uses seven criteria with associated questions to assess the technology; these are shown in Table 1. It should be noted that water treatment is normally used as a multi-barrier approach and disinfection (microbial removal or inactivation) occurs at various stages. The methodology (Figure 1) focuses on the evaluation of disinfection technologies to replace the final stage disinfection process. The criteria are: inactivation efficiency, disinfection by-product formation, toxicity, aesthetic water quality, costs, scalability and residual maintenance. The criteria are ranked in order of importance to the evaluation process. The ranking is based on the regulatory and public health importance of each criterion. The criteria ranked 1 to 4 (inactivation efficiency, DBP formation, toxicity and aesthetic water quality) are all regulated and therefore afford a higher ranking than cost and scalability. Ranking of the first four criteria is based on their perceived importance to public health and current regulatory pressures associated with these criteria. Cost and scalability are intrinsically linked, with cost varying according to scale, as shown in Figure 1. This methodology takes into account that water utilities in countries such as the Netherlands do not always require a residual. The provision of a residual is therefore a discretionary criterion that can be applied as required. It should also be noted that it could be the case that it is appropriate to use a separate disinfectant in addition to the final stage disinfection system to provide the residual. In this case the generation of a residual is of less importance.

The technology is required to meet each criterion in order before it can advance to the next. Failure to meet a criterion at any stage can result in one of two things. The first is to further develop the technology and re-evaluate.



*Other processes during treatment can be used to remove these.

Figure 1 | Flow diagram methodology for the evaluation of disinfection technologies at the final disinfection stage.

Table 1 | Evaluation criteria and questions

Number	Criterion	Question
1	Inactivation efficiency	Does the technology inactivate bacteria, viruses and *Cryptosporidium*?
2	DBP formation	Are the concentrations of DBPs formed lower than the regulatory levels?
3	Toxicity	Is the technology compliant with prescribed drinking water toxicity standards?
4	Aesthetic water quality	Does the technology impair taste, odour and colour?
5	Costs	Are the capital and operational costs of the technology feasible for the company?
6	Scalability	Can the technology be developed from bench and pilot scale technology to an operational technology?
7	Residual maintenance	Does the technology provide a residual for the maintenance of the supply network?

The second is to reject the technology as a plausible alternative to chlorine, either immediately or after the redevelopment/re-evaluation steps. Criteria evaluation is based on the associated UK regulatory standards and a direct comparison with chlorine.

Once the technology has passed each of the criteria it can be submitted for regulatory approval. As it is a requirement for the technology to meet the regulatory standards for each of the criteria the assessor may submit the data from the evaluation process in support of their claim for approval.

The following gives a brief description of each of the criteria and their regulatory standards.

Inactivation efficiency

A variety of pathogens may be transmitted by water, including bacteria, viruses and protozoa. A list of the pathogens known to induce water-borne infections is shown in Table 2.

In addition to the listed pathogens a number of emerging water-borne pathogens have been identified as shown in Table 3. Each of the pathogens has a different level of resistance when subject to disinfection. In the future these emerging pathogens could require regulatory action. It is therefore important that any disinfection technology must be capable of inactivating a range of bacteria, viruses and protozoa.

Table 2 | Pathogens that have been shown to cause infection through contaminated drinking water (DWI 1994)

Bacteria	Protozoa	Viruses
Campylobacter species	*Balantidium coli*	Hepatitis A virus
Escherichia coli (certain serotypes)	*Cryptosporidium* species	Hepatitis E virus
Salmonella species	*Entamoeba histolytica*	Small round structured virus (for example Norwalk virus)
Shigella species	*Giardia intestinalis* (*lamblia*)	Rotaviruses
Streptobacillus moniliformis		
Vibrio species		
Yersinia enterocolitica		

Table 3 | Emerging water-borne pathogens (Jacangelo *et al.* 2002)

Bacteria	Protozoa	Viruses
Aeromonas hydrophila	*Acanthamoeba*	Adenovirus
Helicobacter pylori	Microsporidia	Calicivirus
Mycobacterium avium intracellulare		Coxsackievirus
		Echovirus

The regulation of drinking water quality in the UK is legislated for under the Water Industry Act 1991, the Water Supply (Water Quality) Regulations 2000 and the Private Water Supplies Regulations 2002. The prescribed water quality standards are transposed from the new European Directive 98/83/EC for the quality of water for human consumption (Environment Agency 2002). Under the Water Industry Act 1991 all water supplied to the consumer must be 'wholesome', where wholesomeness is defined by reference to the national and directive-prescribed standards and requirements for microbiological, chemical and physical parameters. The Water Supply (Water Quality) Regulations require the use of indicator organisms including coliform bacteria, *Escherichia coli*, *Clostridium perfringens*, enterococci and colony counts. These organisms are used throughout the world as indicators. In the UK, *Cryptosporidium* oocysts are also monitored as they are considered to pose a particular threat. The prescribed concentrations for these indicator organisms are shown in Table 4.

The Water Supply (Water Quality) Regulations require that drinking water does not contain any concentration of pathogens that would threaten public health (Environment Agency 2002). It is clear that for a technology to be accepted as a viable alternative to chlorination it must be capable of inactivating a variety of pathogens. It is therefore a requirement of the evaluation methodology that data be used for the assessment of inactivation efficiency against a variety of pathogens, with regard to the regulations. It is

Table 4 | The Water Supply (Water Quality) Regulations 2000, water quality standards and requirements

Criteria	Parameter	Concentration	Unit
Microbiological	*Escherichia coli*	0	Number per 100 ml
	Enterococci	0	Number per 100 ml
	Coliform bacteria	0	Number per 100 ml
	Clostridium perfringens	0	Number per 100 ml
	Colony counts	No abnormal change	Number per 1 ml at 1°C
	Cryptosporidium oocysts	<1	Number per 10 litres
DBP formation	Total trihalomethanes *	100	$\mu g\,l^{-1}$
	Tetrachloroethene† and Trichloromethanes	10	$\mu g\,l^{-1}$
	Tetrachloromethane	3	$\mu g\,l^{-1}$
Aesthetic quality	Taste	3 at 25°C	Dilution number
	Odour	3 at 25°C	Dilution number
	Colour	20	$mg\,l^{-1}$ Pt/Co

*The specified compounds are: chloroform, bromoform, dibromochloromethane, bromodichloromethane.
†The parametric value applies to the sum of the concentrations of the individual compounds detected and quantified in the monitoring process.

recognised that *Cryptosporidium* is resistant to chlorination at the concentrations normally employed for disinfection. However, it should be noted that, where *Cryptosporidium* presents a challenge, water treatment processes other than chlorination are required to remove this threat.

Disinfection by-product (DBP) formation

The potential formation of carcinogenic by-products associated with the use of chlorine as a drinking water disinfectant was first identified by epidemiological studies in the late 1970s (Nuckols *et al.* 2001). Since these early findings concern has grown as epidemiological research has continued to link drinking water chlorination with cancer (Bull *et al.* 2001). Hundreds of by-products have been identified in chlorinated drinking water, the most common are the trihalomethanes (THMs), haloacetic acids (HAAs), chloral hydrate, haloacetonitriles, haloketones and chloropicrin (Singer *et al.* 2002). The class of disinfection by-products formed is determined by several factors, including the disinfectant used, pH, organic carbon and bromide content of the treated water. For instance, waters with high concentrations of bromide will tend to form a larger fraction of brominated DBPs. Other research has shown that ozone forms a range of non-halogenated DBPs and brominated DBPs where concentrations of bromide are high Richardson *et al.* 1999).

The UK Water Supply (Water Quality) Regulations 2000 state specific standard values for the presence of total trihalomethanes: that is, the combined concentrations of chloroform, bromoform, dibromochloromethane and bromodichloromethane found at the consumer's tap. The UK standard values are shown in Table 4. It is important that any new disinfection technology is within these limits at its effective dose or operating conditions and that the key by-products are characterised.

Toxicity

If drinking water at the consumer's tap is to be termed 'wholesome' its toxicity must be assessed. Materials, chemicals, by-products and leachates from the disinfection technology must be evaluated to determine their toxicity and concentrations with regard to the Water Supply (Water Quality) Regulations. Regulations 25–28 of the Water Supply (Water Quality) Regulations 2000, require approval of substances, products and processes used in the provision of public water supplies. Approval is carried out on health grounds by the Committee on Products and Processes for use in Public Water Supply (CPP). Where chemicals and materials used in the treatment and supply of drinking water conform to the British Standards Institution standards, they do not require approval (DWI 1999).

The Ames test is frequently used to determine the mutagenic characteristics of compounds and is regularly cited in the UKWIR/WRc-NSF toxicity datasheets. The test utilises special strains of *Salmonella typhimurium* that cannot grow without histidine. Mutagenic compounds will tend to cause a genetic reversion that encourages the organisms to proliferate in the absence of histidine. The number of revertants is used to determine the degree of mutagenicity (Jiang & Lloyd 2002).

Aesthetic water quality

The aesthetic water quality characteristics, taste, odour and appearance are pivotal in consumer perceptions of drinking water. The UK Drinking Water Inspectorate (DWI) 2000 consumer market research found that, of those consumers who do not drink tap water, 46% don't because of the associated taste and smell (DWI 2000). Chlorine is one of the major contributors to drinking water taste and odour. Ideally any replacement disinfection technology should not have an adverse impact on the aesthetic quality of drinking water, meeting the UK standard requirements for aesthetic drinking water quality (taste, odour and colour) shown in Table 4.

Costs

The capital and operating costs of any new technology must be calculated before it can be implemented in the overall treatment process. Where the technology is developed from a concept to a bench scale, to a pilot scale and then to an operational scale project it is likely that the costs will be calculated at each of these stages. The scale of the technology must therefore be taken into consideration when comparing the capital and operational costs of a new technology. The costs of a bench scale technology will obviously differ from those of a large operational process. Therefore care must be taken when extrapolating costs from bench and pilot scale to operational scale technologies.

The economic cost of a new disinfection technology must be evaluated alongside the associated benefits. Operating costs should be in cost per cubic metre of treated water and are normally compared with those of the existing technology, which in most cases will be chlorination. A comparison of the operating cost for several disinfection technologies is shown in Table 5. As the capital costs of the new technologies may vary greatly, it is of importance that the total costs (capital and operational) are considered.

Scalability

A water supplier may receive a technology at a bench, pilot or operational scale. Where the disinfection technology is currently a bench scale technology it is important that data gathered from the aforementioned criteria are available to indicate the feasibility of development to larger scale pilot and operational systems. The data may vary as the technology is developed, thus continuous evaluation is required.

Table 5 | A comparison of disinfection technologies operating costs

Disinfection method	Cost (£ m^{-3})
Chlorine	0.0022–0.01
Ozone	0.01–0.06
Electrochemically generated mixed oxidants	0.001–0.024
Medium pressure UV	0.0019
Electrocoagulation (Electrochemical)	0.014
Photodynamic disinfection	0.0256
Pulsed electric fields (PEFs)	0.0266
Advanced low pressure UV	0.204
Titanium dioxide photocatalysis	0.26
Irradiation	0.38
Solar- titanium dioxide photocatalysis	0.45
Hydrodynamic cavitation	0.85

Residual maintenance

The maintenance of a disinfectant residual in the supply network is important for two reasons. The first is the control of microbial regrowth in the supply network. The second, in systems with higher residuals, is the inactivation of microbial contaminants entering the system (LeChevallier 1998). A residual disinfectant may also aid in the prevention of biofilm formation and serve as a sign of contamination where the residual is destroyed (Trussell 1998). The level of residual required is largely dependent on the nature and condition of the source water and the distribution system (Hydes 1998). The presence of organics and corrosion in the distribution system will remove oxidant residuals from the system. It is therefore important that the water supplier is able to demonstrate the effect of different water quality parameters on the stability of the residual.

The presence of a residual disinfectant is not a requirement in all countries. For instance, in the Netherlands only 21.2% of drinking water goes through a final chemical disinfection treatment stage. The remainder of drinking water is abstracted from groundwater within special protection zones. The groundwater is filtered through aquifers composed of layers of sand, peat and clay, is treated by a multi-barrier treatment process and is then distributed in a uPVC distribution system, all of which results in biostable drinking water that does not require a residual disinfectant (Gale *et al.* 2002).

Additional environmental considerations

Sustainable development is a concept that is increasingly employed in the decision-making process. The most accepted definition of sustainable development is that of the Brundtland Commission, 1987, ‘to meet the needs of the present without compromising the ability of future generations to meet their own needs’ (Bulleit 2000). It is important that the future environmental and social implications of the development of new disinfection technologies are considered when evaluating their potential as a replacement for chlorination. Each criterion has a number of environmental issues associated with it. The environmental implications of new disinfection technologies therefore need to be evaluated at each stage of the methodology (Figure 1). An overall assessment of impact on the environment should also be made to enable a comparison between technologies.

A life cycle approach helps to determine the environmental impacts of products and/or services from cradle to grave. In the case of disinfection, such an approach would enable a greater understanding of the impacts of factors such as energy usage and generation, and transportation and storage of chemicals. For example the disinfectant chlorine gas is transported and stored as a liquid under pressure in cylinders. The transportation and storage of strong oxidants is a concern both in terms of environmental and social impacts associated with the potential escape of the oxidants and the overall effect of transportation on the environment.

Energy is another issue that requires consideration in the evaluation process. Although energy is partly dealt with in the cost criteria, with energy intensive technologies tending to have a high operational cost, the generation of energy from sources such as hydrogen in electrochemical disinfection processes are quite often ignored. Thus, it is important that the total energy contribution of the disinfection process is assessed and utilised where feasible to offset cost.

RESULTS AND DISCUSSION

Case study: UV disinfection

The following discussion will use ultraviolet disinfection as an example to demonstrate the evaluation methodology in practice. Each question in Table 1 will be addressed in accordance with the methodology shown in Figure 1.

Question 1. Inactivation efficiency

The evaluation of inactivation efficiency would be a phased approach based on the regulatory indicator pathogens shown in Table 4, and known virus indicator species. Evaluation standards use chlorine as a comparison. US Benchmark standards require total inactivation of bacteria, 4 log inactivation of viruses, a 3 log inactivation of *Giardia lamblia* cysts (US EPA Surface Water Treatment Rule 1989) and a 2 log inactivation of *Cryptosporidium* (US EPA Interim Surface Water Treatment Rule 1998). However, as previously discussed it is expected that other disinfection processes are required to remove *Giardia* and *Cryptosporidium*. Any additional inactivation at the final disinfection stage could be seen as an added advantage of the disinfection technology.

Ultraviolet (UV) disinfection has been shown to be as effective as chlorine at inactivating a range of bacteria and viruses (Lazarova *et al.* 1999). Against *Cryptosporidium* oocysts UV is effective at doses as low as 9 mJ cm^{-2} with a (3 log inactivation (Rose *et al.* 2002). In comparison UV at similar doses (9.3–11.7 mJ cm^{-2}) has been shown to result in a 2 log inactivation of *Giardia lamblia* cysts (Campbell & Wallis 2002). Problems associated with UV disinfection are microbial DNA repair by photoreactivation and dark repair (Lazarova *et al.* 1999; Morita *et al.* 2002), each of which may allow regrowth in the supply network. Water with high total suspended solids can also pose a problem because of the reduced UV transmittance, which results in a need for longer contact times to deliver the required dose (Hoyer 1998). A similar effect is seen for chlorine with high concentrations of organic particles, which increase chlorine demand and concentration × contact time (CT) values required for disinfection.

Question 2. Disinfection by-product formation

The benchmark standards for disinfection by-product formation are the regulatory standards shown in Table 4. The evaluation procedure would include a direct comparison of DBP formation between the disinfection technology and chlorine for a selected water matrix. The new technology should generate lower DBP concentrations than the regulatory standards and should ideally generate concentrations lower than chlorine.

No significant formation of disinfection by-products has been shown for water and wastewater treated with medium and low pressure UV systems (Lazarova *et al.* 1999; Rose *et al.* 2002). In fact, UV irradiation can act to reduce the formation potential of trihalomethanes (THMs) (Kleiser & Frimmel 2000) by breaking down organic precursors.

Question 3. Toxicity

Disinfected water must be fit for public consumption. Benchmark toxicity standards for compounds in disinfected water should be taken from national standards where possible or from WHO guideline values and/or UKWIR/WRc-NSF toxicity datasheets. Where standards or guidelines do not exist toxicity tests for the assessment of health risks should be conducted.

UV disinfection is a physical process that does not rely on the addition of chemicals to water. As previously mentioned no toxic disinfection by-products have been found in UV treated waters. UV irradiation has been used for disinfection since the early 1900s (Rose *et al.* 2002) and is currently used for small-scale potable water disinfection. UV disinfection will therefore be compliant with respect to the UK Water Supply (Water Quality) Regulations (2000).

Question 4. Aesthetic water quality

The benchmark standards when assessing the aesthetic quality of disinfected water are the regulatory standards for taste, colour and odour shown in Table 4. It is advised that a direct comparison of aesthetic water quality between water treated with chlorine and water treated with the alternative disinfection technology is made.

Organic compounds in water can have negative effects on colour, odour and taste (Chang *et al.* 2001). The ability of UV irradiation to degrade these compounds will change the aesthetic characteristics of the water. As no residual disinfectant is produced during UV disinfection, regrowth and biofilm formation is likely to affect aesthetic water quality where the supply network is aged. The presence of biofilms in the distribution network can be responsible for off-flavours and contribute to discoloured water (Environment Agency 2002).

Question 5. Costs

There is no benchmark for the capital cost of a new disinfection technology. Each drinking water provider must determine whether a technology is economically feasible. However, for operational cost, the cost of chlorine disinfection can be used as the benchmark. A direct comparison should be made between the cost of one cubic metre of water treated by the new technology and by chlorine.

The capital cost of UV disinfection will be largely dependent on the required capacity, size of plant, the characteristics of the water to be treated and the type of lamp required, either medium or low pressure. The operating cost of UV disinfection is competitive with chlorination with a cost of £0.0019 per m^3 of treated water compared with £0.0022 per m^3 of treated water with chlorine. The operating costs will depend on power consumption, lamp cleaning and the replacement of equipment such as lamps ballast and sleeves (Solomon *et al.* 1998).

Question 6. Scalability

There is no benchmark scale for disinfection technologies. Whether a technology passes this criterion is dependent on the requirements of the water provider and whether the technology is effective at the desired scale and the cost implications of scale-up.

Ultraviolet disinfection technologies have been applied in both large-scale (Chu-Fei *et al.* 1998; Rose *et al.* 2002) and small-scale experimental (Morita *et al.* 2002) and point-of-use (Huffman *et al.* 2000) water and wastewater treatment plants. The successful adoption of UV disinfection as a replacement for chlorine dioxide in the Petersaue water treatment works, Germany, is an example of the use of UV disinfection for large-scale treatment (Schredelseker *et al.* 1998). Thus, there is no doubt that UV disinfection technologies can be scaled for operational purposes where the water properties are appropriate.

Question 7. Residual maintenance

The benchmark for the provision of a residual will vary according to the country's regulations. In the UK, specific residual concentrations are not required. The residual will depend on the quality of the source water and the condition of the distribution system. Residual concentrations should, however, ensure microbiological standards, minimise disinfection by-product and biofilm formation, and limit the impact on aesthetic quality.

UV disinfection does not provide a residual disinfectant. This may be acceptable in areas where residual maintenance is not a legal requirement and where the integrity of the supply network can be maintained without a residual. However, in supply networks where a residual is required UV may be used as the primary disinfectant combined with a residual chemical disinfectant. This will, however, add to the cost of the process and would not necessarily result in an improvement in the aesthetic quality of the distributed water.

Additional environmental considerations

As discussed earlier a life cycle approach should be used to evaluate the environmental implication of new disinfection technologies. Where possible a life cycle assessment (LCA) should be conducted to compare the socio-environmental impacts of the new disinfection technology with chlorine.

As UV disinfection is a physical process, no generation, handling, transportation or storage of toxic or hazardous chemicals are required.

Summary

Ultraviolet disinfection fulfils the majority of criteria required for a disinfection technology with the exception of the provision of a residual. Clarification is needed on the impacts of microbial DNA repair, to fully assess the possibility of microbial regrowth in the supply network. Where a residual disinfectant is required research is necessary to identify a residual disinfectant that complies with the criteria shown in the methodology.

EVALUATION OF THE ALTERNATIVE DISINFECTION TECHNOLOGIES

The following work uses the methodology to evaluate some of the alternatives to chlorination based on the literature. Table 6 summarises the results for each of the technologies based on the seven criteria used in the methodology. The results illustrate some of the uncertainties and limitations that need to be overcome before these technologies can be accepted as suitable alternatives to chlorination.

Technologies such as ozone and UV disinfection are presently operational and offer proven safe primary disinfection without the residual capabilities. These technologies may, however, have competition from two alternative technologies – direct electrochemical disinfection and mixed oxidant generators – that are emerging as having the potential to provide both primary and residual disinfection. The application of these technologies may be hindered by their potential for chlorine production. It is feasible that optimisation of the processes could either limit or prevent the generation of chlorine species. More research will be needed before these technologies can be put into full-scale operation.

CONCLUSION

A methodology has been devised that enables the evaluation of alternatives to chlorination for the disinfection of potable water. Seven criteria have been identified as measures of the technology's acceptability as an alternative to chlorination. These criteria are: inactivation efficiency, disinfection by-product formation potential, toxicity, aesthetic water quality, cost, scalability and residual maintenance. These criteria are assessed in order of importance to the water supplier and are related to water quality regulations.

Ultraviolet disinfection has been used as an example to evaluate the methodology. It is shown that UV irradiation meets all criteria apart from the provision of a residual disinfectant. Where a residual disinfectant is not required, or a chemical residual may be applied, UV is an acceptable alternative to chlorination.

A number of the alternatives to chlorination have been assessed using the methodology developed in this paper and the uncertainties and limitations for each of the technologies have been identified. Two technologies, direct electrochemical disinfection and mixed oxidant generators, have been recognised as potential future replacements for chlorine.

Table 6 | Evaluation of the alternative technologies to chlorination

	Inactivation efficiency						Scalability				
Disinfection technology	**Bacteria**	**Viruses**	***Crypto***	**DBP formation**	**Toxicity**	**Aesthetics**	**Costs**	**Bench**	**Pilot**	**Ops**	**Residual**
Ozone	✓	✓	✓[a]	✓[c]	✓	✓	✓	✓	✓	✓	×
Ultraviolet light	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×
Direct electrochemical	✓	#	?	✓[e]	?[d]	✓[e]	✓	✓	✓	?	✓[e]
Mixed oxidant generators	✓	✓	✓	✓[e]	✓	✓[e]	✓	✓	✓	✓	✓
TiO_2 photocatalysis	✓	✓	#	✓	?	?	×	✓	✓	?	×
Irradiation	✓	✓	#	✓	✓	✓	×	✓	✓	?	×
Pulsed electric fields	✓	#	#	✓	?	?	×	✓	✓	?	×
Sonication	✓	#	#	✓	✓	✓	×	✓	?	?	×
Metal ions Au/Ag/Cu)	✓	✓[ab]	?	✓	✓[d]	×[a]	?	✓	✓	?	✓[c]
Ferrates	✓	✓	?	✓	✓	?	?	✓	?	?	×

✓Meets the criteria.
×Does not meet the criteria.
?Not reported in the literature.
#Only a few examples reported in the literature, effective dosing range is unclear.
[a] High CT (disinfectant concentration × contact time) required for effective kill.
[b] Doses may be above the maximum contaminant levels (MCL) if used alone, when used in combination this is not a problem.
[c] Residual capacity scavenged by organics.
[d] Dependent on electrode material.
[e] Dependent on whether chloride is used in the electrolyte.
[f] Bromate will be formed in bromide-containing waters.

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