Disinfection Technology and Alternative Disinfection for Commercial Water

August 2025

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FINAL REPORT

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Glossary

AWWA	American Water Works Association
CCF	Ceramic Candle Filter
DBP	Disinfection byproduct
DWI	Drinking Water Inspectorate
DWQR	Drinking Water Quality Regulator
GAC	Granular Activated Carbon
HAA	Haloacetic Acid
HWT	Household Water Treatment
LPUV	Low-pressure Ultraviolet
MCA	Multi-criteria Analysis
MCDA	Multi-criteria Decision Analysis
MPUV	Medium-pressure Ultraviolet
NOM	Natural Organic Matter
OSE	On-site Electrolysis
RO	Reverse Osmosis
SEPA	Scottish Environment Protection Agency
THM	Trihalomethane
USEPA	United States Environmental Protection Agency

Summary

i Reasons

The Drinking Water Inspectorate (DWI) wished to gain a better understanding of the disinfection technologies currently in use on commercial activities across England and Wales, including alternative technologies, and their suitability for ensuring safe drinking water. Additionally, they would like to identify alternative technologies which are being used internationally and assess their suitability for use in England and Wales.

ii Objectives

- To discuss and define what the term ‘commercial activities’ implies within the context of the project.
- To collate and analyse information regarding the types of disinfection technologies used on private and public water supplies in England and Wales, and the types of activities fed by private water supplies
- To evaluate disinfection technologies used on private and public water supplies in England and Wales. This included a multi-criteria analysis to systematically compare and rank the performance of selected disinfection methods
- To provide an overview of alternative disinfection technologies used internationally and to make recommendations about their suitability for use in England Wales

iii Benefits

The results of this report will enable the DWI to provide more effective guidance to local authorities and water companies on the use of widespread and alternative disinfection technologies and whether alternative methods are suitable for ensuring safe drinking water.

iv Conclusions

Context of the term commercial applications
In the context of the private water regulations for England and Wales, a commercial activity/premise/application is where potable water derived from a private supply system is consumed by a commercial activity. Examples include during food or drink production intended for human consumption, or a hotel using a private water supply for domestic purposes. In contrast, public applications or activities are where potable water from a private supply is available for public consumption. This includes public buildings such as education providers, hostelries and exhibitions.

DWI and WRc agreed that the distinction between public and commercial applications is often unimportant from a regulatory or public health perspective. Therefore, it was decided that both were within the project scope. Moreover, it was agreed that public water supplies were within the project scope, defined in this context as situations where activities practice disinfection of a public water supply before onsite distribution.

Local authority surveys and water company enquiries

In England and Wales, local authorities act as regulators for private water supplies, with DWI acting as technical advisors. A total of 118 English and Welsh local authorities responded to two surveys sent out during the project. All 10 technologies noted by survey respondents as being used for the disinfection of private water supplies were selected for inclusion in subsequent project stages.

The two most-widespread technologies for disinfection of private water supplies were UV irradiation and hypochlorite, mentioned as being in use in respectively 77% and 41% of local authority areas across both surveys. Chlorine dioxide was in use in 12% of local authority areas, while the seven remaining technologies - hypochlorite generated by onsite electrolysis of brine (OSE), chlorine gas, chloramines, ozone, hydrogen peroxide, reverse osmosis and ceramic candle filters (CCFs) - were in use in ≤8% of areas.

CCFs were installed as the sole form of disinfection on private water supplies within three local authority areas. In two of these local authority areas, samples treated by CCFs had failed water quality regulations, which raises concerns about the use of this method as a sole treatment/disinfection step on private water supplies.

A wide variety of activities using private water supplies were mentioned by survey respondents; the three commonest categories being types of accommodation, tenanted properties let on a commercial basis and businesses selling food and drink.

Responses from four municipal water supply companies highlighted that care homes and hospitals are likely to practice onsite disinfection of public water supplies, using technologies including reverse osmosis, chlorine dioxide and hydrogen peroxide dosing.

Multi criteria analysis (MCA) of disinfection technologies used in England and Wales

Six criteria were used in the final MCA: operational cost, ease of asset management, disinfection byproducts (DBPs), efficacy against microorganisms (split into three sub-criteria, relating to bacteria, protozoa and viruses), footprint and health and safety. The highest weighting of 0.45 (0.15 for each sub-criterion) was given to microbial efficacy, reflecting its critical importance for public health.

Hypochlorite solution was the highest ranked disinfection technology, primarily due to its strong scores in microbial efficacy, operational cost, and ease of asset management. However, this chemical can result in relatively high concentrations of DBPs. UV irradiation ranked second. It performed well across multiple criteria but with relatively high operational costs and asset management challenges.

Chlorine dioxide, reverse osmosis, ozone, and chlorine gas were all regarded as effective disinfectants, but their overall ranking was lower than UV irradiation and hypochlorite because they performed comparatively poorer for certain criteria, such as ‘ease of asset management’.

Chloramines and CCFs were the lowest ranked technologies, reflecting their relatively low scores under ‘microbial efficacy’. The MCA outcome indicates both technologies are best suited as supplements to other disinfection technologies, rather than as a primary disinfectant.

Disinfection technologies used overseas
The suitability of physical, chemical, thermal, solar and combination treatment approaches used overseas were assessed as potential disinfection methods for use in England and Wales. Of these, ultrafiltration technologies, mixed oxidant solution and peracetic acid warrant further investigation. Bromine is a promising alternative to chlorine, but there are concerns over the formation of high levels of brominated DBPs.

v Recommendations

- Modified risk assessment and/or guidance should be considered where CCFs or chloramines are the sole disinfectant technology for private or public water supplies in England and Wales.
- Ultrafiltration technologies, mixed oxidant solution and peracetic acid warrant further investigation before application to public and private water supplies in England and Wales.
- Clarify the potential health risks associated with bromine (including brominated DBP formation) ahead of bromine being considered for use as a disinfectant in England and Wales.

1. Introduction

1.1 Background

The primary aim of this project was to investigate and assess the disinfection technologies employed in commercial applications, including hospitals, prisons, army bases and food processing factories. These commercial applications can be supplied by either private or public water supplies in England and Wales, with disinfection taking place onsite. Information was requested from both local authorities and water companies regarding commercial applications fed by respectively private and public water supplies, though because only limited information was received from the latter, there is more focus on private supplies in this study.

The DWI became aware there may be alternative disinfection technologies and equipment being marketed for use in England and Wales. The DWI required an independent review of the available technologies currently installed in commercial applications, including the performance thereof where available. Further, a need was identified to review technologies used overseas that may be suited to use in England and Wales. This information will be used to provide guidance about the use of disinfection technologies, potentially including to local authorities for assessing those in use within their areas.

1.2 Objectives

Specific objectives of the project were as follows:

1. **To discuss and define what the term 'commercial applications' implies within the context of the project, in particular to:**

    - Discuss the context of the term "commercial applications" in a workshop involving DWI and WRc and agree the relevance of this term to the project scope.
    - Discuss the relevant regulatory background and provide examples of commercial applications.

2. **Design and disseminate surveys to local authorities in England and Wales. These surveys had the following purposes:**

    - To obtain a representative picture of the types of disinfection technologies currently being used to treat private water supplies in England and Wales,
    - To obtain a representative picture of the types of activities supported by these supplies.

- To select a representative list of disinfection technologies to review and analyse in subsequent stages of the project

3. **Critically review the performance of disinfection technologies currently used in England and Wales, with a focus on efficacy for removal and/or inactivation of microorganisms. This included the following aspects:**

- Summarise the scientific principles by which each technology acts as a disinfectant
- Collate the potential benefits and limitations of each technology
- Collate and analyse literature regarding the microbial efficacy of each selected technology
- Summarise other literature regarding disinfection byproduct formation and practical considerations for each technology, including ease of operation, health and safety risks and economics.

4. **Undertake a multi-criteria analysis to compare and rank the performance of disinfection technologies currently used in England and Wales.**

This included scoring each technology against the following six criteria:

- Operational cost
- Ease of asset management
- Disinfection byproducts
- Microbiological efficacy against:
  - Bacteria
  - Protozoa
  - Viruses
- Footprint
- Health and Safety

5. **Critically review the disinfection technologies applied to public and private water supplies internationally, and to assess their suitability to private water supplies in England and Wales. 'International' was defined as the following geographical areas: Global (including developing countries), the European Union, North America (USA/Canada), and Australasia (Australia/New Zealand).**

   This task included the following components:

   - Literature search of regulatory documents, national guidelines, national/international standards, academic literature (if applicable), and any other relevant material relating to the disinfection of drinking water supplies was gathered for the four geographical areas listed above.
   - Collate the potential benefits and limitations, including microbial efficacy, of selected technologies via literature.
   - Assessing the suitability of selected technologies for disinfection of drinking water supplies in England and Wales, in the context of their advantages/disadvantages as disinfection methods and microbial efficacy.

2. The context of 'commercial' applications

2.1 Approach

The given title for this project is "Disinfection technology and alternative disinfection for commercial water", which is the same as used in the initial 'invitation to tender'. The term 'commercial water' may encompass related terms "commercial use", "commercial application", "commercial activity" and "commercial premises", as commonly used but loosely defined in relevant regulations for private water supplies. Discussion and agreement of which regulatory definitions would apply to this project was necessary, as this would impact the types of water sources and potential technologies considered

WRc hosted an initial workshop with DWI to discuss the definitions used in regulations for the purpose of establishing the scope of work. In this workshop the regulatory background, and various definitions, were discussed, with the intention of agreeing the relation of this term to the scope of the project.

2.2 Supplies covered by private water regulations

In England and Wales, local authorities act as regulators for private water supplies and are responsible for monitoring and undertaking risk assessments, to ensure compliance with drinking water standards. Meanwhile, DWI act as technical advisors to the local authorities. The Private Water Supplies (England) Regulations (2016) apply to private supplies of water intended for human consumption in England. In Wales, the equivalent piece of legislation is The Private Water Supplies (Wales) Regulations (2017). Both regulations require local authorities carry out risk assessments to establish any potential negative impact on human health from private supplies in their area. Regulations 8-11 provide further detail regarding the types of supplies covered by the private water regulations in both England and Wales.

2.2.1 Regulations 8 – 11 of the private water regulations for England and Wales

Regulation 8 covers supplies in which water is initially taken from a water company and then further distributed by a party other than the water company. Regulation 9 covers supplies for either commercial or public use in which an average of over 10m^3 of water is used per day for domestic purposes, or any supply where water is used in a public or commercial activity.

In respect to Regulation 10, the English and Welsh private water regulations diverge slightly. In England, a Regulation 10 supply is defined as any private water supply not covered by Regulation 8 or 9. This includes domestic supplies using <10 m^3/day. Local authorities must monitor these supplies at least every five years and more frequently if required by the risk assessment. For single dwellings, local authorities must monitor these if requested to do so by the owner or occupier.

In Wales, Regulation 10 applies to single dwellings which are not used as part of a commercial or public activity (in which case regulation 9 applies) or as part of a domestic tenancy (in which case regulation 11 applies). The local authority must monitor these types of supplies at least every five years and more frequently if the risk assessment shows this to be necessary or if requested to do so by the owner or occupier.

Regulation 11 applies to Wales only and is defined as any private water supply not covered by Regulations 8, 9 or 10. Local authorities must monitor these supplies at least every 5 years and more frequently if required by the risk assessment or if requested to do so by the owner or occupier.

2.3 Examples of commercial and public activities

It should be noted that what constitutes a commercial (or public) activity, application or use, is **NOT** defined in either the English or Welsh regulations. This is because the nature of the activity supplied, and whether it is commercial nor not, is not necessarily relevant in the context of the regulations.

DWI has issued two guidance notes which discuss Regulation 9 of the English and Welsh private water regulations (DWI, 2022) and what constitutes a commercial premises (DWI, 2014) in the context of these regulations. Sections 2.3.1 and 2.3.2 use information from these guidance notes. They clarify how certain activities, such as food production and businesses, are categorised. Additionally, it highlights specific conditions under which tenanted properties are considered commercial activities.

2.3.1 Examples of commercial activities

Under Regulation 9 of both English and Welsh regulations, a commercial activity, premise or application can be thought of as any property where the landlord or owner retains, or choses to keep, responsibility for a system supplying water which is then consumed as part of a commercial activity (DWI, 2014 and, 2022). Some illustrative examples of commercial activities are given below in Table 2.1.

Table 2.1 Examples of commercial activities in the context of English and Welsh private water supplies (DWI, 2022)

Category	Details or specific examples
Food and drink production	Where a private water supply is used in the production of food or drink intended for human consumption
Businesses using a private water supply for domestic purposes	Hotels, guest houses, restaurants, cafes, bed and breakfasts (B&Bs), holiday lets, caravan sites, campsites, registered child minders.

Category	Details or specific examples
Tenanted properties	Only when the following criteria apply: (i) the landlord/owner is offering accommodation which could not be let without a private water supply, (ii) the tenant(s) does not have full responsibility for water supply and (iii) the let has a commercial element.
Business offices	Only when the business is selling products containing water from the private supply. See text below.

If a business is selling products containing water from the private supply, then this would be classed as a commercial activity within Regulation 9 (large and/or commercial supply). If the business workers and offices are consuming 10m^3/day or less from the private supply for any domestic purposes, without being charged a fee, then the supply is subject to the requirements of Regulation 10. (DWI, 2022).

2.3.2 Examples of public activities

Private supplies that form part of a public activity are those serving any premises where the water is made available to the public for human consumption (DWI, 2022). This includes public buildings, such as the illustrative examples given in Table 2.2.

Table 2.2 Examples of public activities in the context of English and Welsh private water supplies (DWI, 2022)

Category	Specific examples
Education	Schools/colleges, further educations, universities, nurseries
Hostelries	Cafes, pubs, restaurants, hotels and inns, guest houses, wine bars, campsites
Exhibitions	Museums, art galleries, exhibition centres, conference centres
Leisure	Sports stadia, leisure centres, health clubs, tourist attractions, night clubs, theatres, ice rinks, cinemas, historic buildings
Miscellaneous	Hairdressers, beauty salons, prisons/detention centres, community centres, job centres

2.4 Agreed project scope

Discussion between WRc and DWI during the first project workshop highlighted that the definitions of commercial and public applications are sometimes unclear in the context of the English and Welsh Private Water Supply Regulations (2016, 2017). It was agreed that the distinction between public and commercial applications is not always important from a regulatory perspective, because the monitoring parameters and frequency are the same for both. In particular, both public and commercial supplies fall within Regulation 9 of the private water regulations for England and Wales. Furthermore, it was commented that the distinction is also not important from a public health perspective. Therefore, it was agreed during the first project workshop that disinfection technologies used with both commercial and public applications, in the context of private water regulations for England and Wales, would be within the project scope. This means that the surveys sent to local authorities regarding types of disinfection technologies in use with private water supplies, did not need to distinguish between public and commercial applications.

A more important distinction was raised between public and private water supplies, in the context of Regulation 8 of the private water regulations for England and Wales (2016, 2017). As described in Section 2.2.1, Regulation 8 applies to water taken from a water company and then further distributed to a third party by an entity other than the water company. However, where a public water supply is treated and distributed onsite (i.e. without any onward distribution), then this would no longer fall within the jurisdiction of Regulation 8 and would not be subject to local authority monitoring. An example of this type of situation would be where a building, such as a hospital or office/apartment block, has an onsite water storage tank and the water receives some form of disinfection, e.g., chlorination or UV irradiation, at the inlet or outlet before being further distributed onsite.

While there is no indication this type of situation would deploy different disinfection technologies to those used with private water supplies, it was agreed that WRc would make an information request via its Disinfection Forum, which currently counts 16 water companies as members. While water companies are not responsible for the design and operation of disinfection technologies used in private water supplies, they may have acquired some knowledge of installations through undertaking monitoring at customers' taps, or in their role as regulators for the Water Supply (Water Fittings) Regulations (1999). The outcomes from these enquiries are described in Section 3.3.

3. Local authority surveys and water company enquiries

3.1 Background and methodology

During the project, information was requested from both local authorities and water companies regarding commercial applications fed by respectively private and public water supplies. Because only limited information was received from the latter, there is more focus on private supplies in this section.

Surveys were sent out to local authorities across England and Wales, as a starting point, to provide an overview of the types of public and commercial activities fed by private water supplies and of the types of disinfection technologies used in this context. In the first project workshop between WRc and DWI it was agreed to disseminate two online surveys, using Microsoft Forms, to local authorities in England and Wales. DWI provided a cover letter demonstrating their support for the survey and shared generic contact email addresses for local authorities across England and Wales.

Survey 1 consisted of nine questions and was sent to a list of existing WRc contacts within local authorities while the longer list of respondents for Survey 2 was being prepared and approved within DWI. Survey 2 had eleven questions. The full list of questions for Survey 1 and Survey 2 can be found in Appendix A. The questions asked were similar across both surveys, although in Survey 2 respondents were asked to state their local authority and email address. All were asked about the number of private water supplies, type of disinfection technologies used and the types of activities in the area.

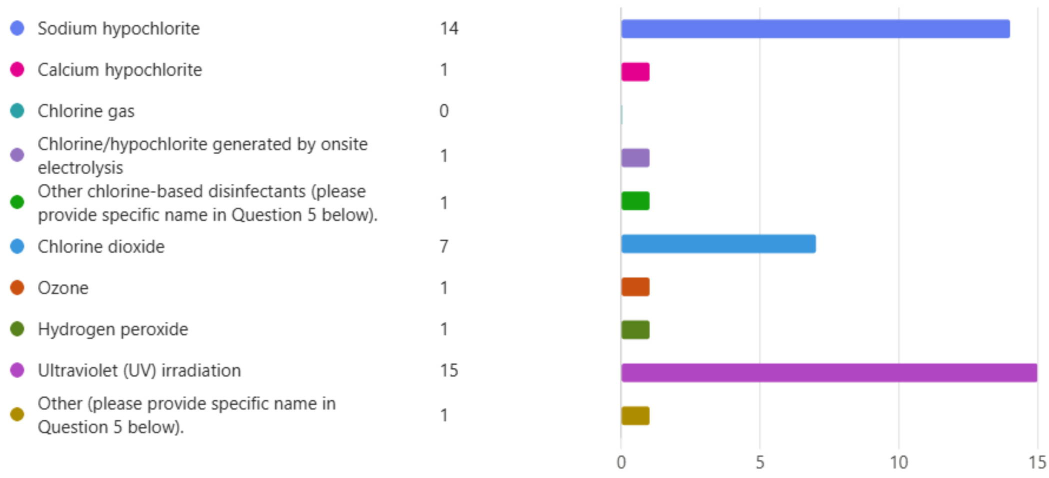
Survey 1, targeted at existing WRc contacts, was sent to 20 local authority employees known to have an active interest in private water supplies as of December 2024. During January 2025 DWI provided more than 400 generic local authority environmental health email addresses and asked WRc to contact at least 100 of these. Recipients of Survey 1, duplicate entries and those who hadn't given permission to be contacted, were all removed from the list. Survey 2 was disseminated to the remaining 264 generic local authority environmental health email addresses later that month.

3.2 Results from surveys

3.2.1 Survey 1 – Disinfection Technologies

Survey 1 was completed by 17 out of 20 local authorities (85%). Sodium hypochlorite and ultraviolet irradiation were the most common disinfection technologies, mentioned by respectively 14 and 15 respondents as being used in their local authority areas (Figure 3.1). Multiple respondents reported ultraviolet irradiation was the most common disinfectant used in their area. Chlorine dioxide was mentioned by seven respondents as being used in their local authority area, while calcium hypochlorite, chlorine generated by onsite electrolysis, ozone and hydrogen peroxide were all identified by a single respondent (Figure 3.1). Note that we report only the number of respondent local authorities, not the number of private water supplies using a particular disinfection technology in local authority areas.

Figure 3.1 Disinfection technologies mentioned in Survey 1



Free-text boxes encouraged the reporting of additional information (Table 3.1). Respondents identified reverse osmosis and ceramic membranes were also in use.

Table 3.1 Free text comments from Survey 1

Selected free text comments
Vast majority of our supplies use UV only, but we have 11 supplies who use chlorine-based disinfection.
Most of our supplies use conventional disinfection techniques. We have just one whiskey distillery which uses hydrogen peroxide and the Dwi (*sic.*) have been made aware of this.
The majority of disinfectant technologies used by private water supplies are ultraviolet treatment.
Microfiltration - 10, 1, 0.45, 0.2 micron filters made by Spectrum. Only one drinks manufacturer that uses this.
Reverse Osmosis. Ceramic candle/membrane.

3.2.2 Survey 1 – Activities

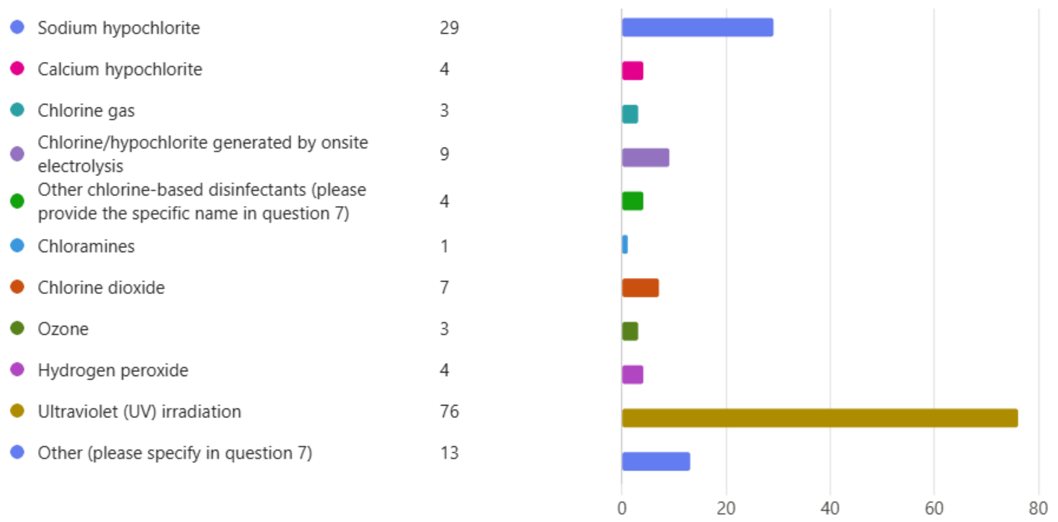
A wide variety of activities using private water supplies were mentioned by Survey 1 respondents, the commonest being various types of accommodation, food production and manufacture, tenanted properties let on a commercial basis and businesses selling food and drink (Figure 3.2).

Figure 3.2 Activities using private water supplies mentioned by Survey 1 respondents

3.2.3 Survey 2 – Disinfection technologies

There were 101 responses to Survey 2. Ultraviolet irradiation was overwhelmingly the commonest technology mentioned, by 76 respondents, with sodium and calcium hypochlorite combined mentioned by 33 respondents (Figure 3.3). Other technologies mentioned by a smaller number of respondents were chlorine gas, hypochlorite generated by onsite electrolysis, chlorine dioxide, ozone and hydrogen peroxide (Figure 3.3). One important difference from Survey 1 was that chloramines were mentioned as a disinfectant technology by one respondent (Figure 3.3), whereas this technology was not mentioned during Survey 1 (Figure 3.1 and Table 3.1).

Figure 3.3 Disinfection technologies mentioned in Survey 2



Similar to Survey 1, various types of membrane filtration - CCFs, microfiltration and reverse osmosis – were mentioned by Survey 2 respondents in the free text comments during the survey, while it was also noted that a small number of individual households fed by private water supplies had no treatment (Table 3.2).

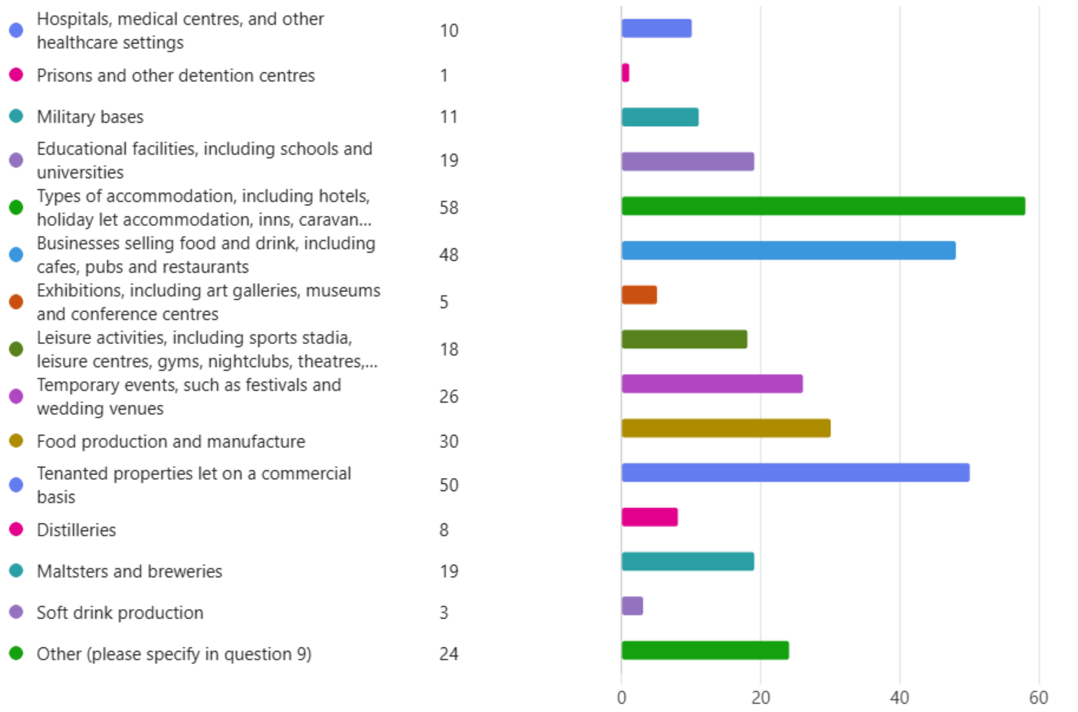
Table 3.2 Free text comments from Survey 2

Selected free text comments
Ceramic candle filters (CCFs)
Reverse Osmosis
0.5 micron filter
Reverse Osmosis
We do not record specific treatment types other than UV and chlorination. We have a few ceramic candles, we have a few supplies that use micron filters only and some that use no treatment.
Our 10 supplies are each to individual homes - and some I think have no treatment - i.e. the water is just used 'as is' - as it comes from the ground.

3.2.4 Survey 2 – Activities

A wide variety of uses were reported by Survey 2 respondents, in common with Survey 1. Accommodation, tenanted properties let on a commercial basis, and businesses selling food and drink were the three most-common reported activities (Figure 3.4).

Figure 3.4 Activities using private water supplies mentioned by Survey 2 respondents



3.2.5 Selection of drinking water disinfection technologies

All technologies reported by the 118 English and Welsh local authority respondents as being used for the disinfection of private water supplies were included in the literature review. For the multi-criteria analysis, technologies were categorised as follows:

1. Hypochlorite solutions, incorporating calcium hypochlorite solution/tablets/powder and sodium hypochlorite solution

2. Hypochlorite solution, generated by onsite electrolysis of brine (OSE)

3. Chlorine gas

4. Chlorine dioxide

5. Chloramines

6. Ozone

7. Hydrogen peroxide

8. Ultraviolet (UV) irradiation

9. Reverse Osmosis

10. Ceramic Candle Filters (CCFs)

3.2.6 Follow-up investigations from survey results

Results were presented to the DWI in a second workshop. During the associated discussion the DWI requested WRc clarify with local authorities certain aspects of the use of CCFs and chloramination:

1. **Ceramic candle filters (CCFs)**. Reverse osmosis and nanofiltration are known to be highly effective disinfectants, the pore size blocking known pathogenic organisms. However, the larger pore size of microfiltration, as used in CCFs, reduces disinfection efficacy. It was necessary to establish whether CCFs are used as a sole barrier in all three areas reporting their use. Respondents confirmed CCFs were the sole treatment and disinfection barrier in some instances (Table 3.3). Also, microbiological breaches were reported in Pendle and East Devon. This raises clear concerns about the choice, installation and maintenance of CCFs.

Table 3.3 Details about CCFs in all local authorities reporting their use

Local authority	Selected comments
East Devon	From memory ceramic candles were the only form of treatment and the supply failed the sample collected for bacterial contamination. They were supposedly cleaned regularly but there were no records of this or any procedures.
Monmouthshire	We have some properties (mainly domestic properties as part of a larger supply) that use only ceramic filters. A small number of properties have both UV and a ceramic filter.
Pendle	One village has a spring supply and residents opted to fit ceramic candle filters rather than UV because they were simpler to install. So they're being used as the sole means of treatment. Most seem to be working well. I had a failure a couple of years ago and it turned out that the ceramic had cracked, so I advised everyone to periodically examine for defects. It also transpired that this particular filter had been fitted with the water flow in the wrong direction.

2. **Chloramines**. Chloramine (NH_2Cl) is known to be less effective than 'free' chlorine ions (Cl_2^-) against the common range of pathogenic microorganisms. It is less common as a disinfectant than chlorine in both municipal and private water supplies. For municipal water treatment in England and Wales, typical application involves first exposing water to free chlorine for a designated contact time measured in minutes (referred to as 'Ct' in the water

industry) before adding ammonia to generate monochloramines in distribution. Chloramines provide a weak, but persistent, disinfectant suited to lengthy distribution residence times. There was discussion regarding whether the same applies when chloramines are dosed directly into private water supplies (i.e. following exposure to free chlorine for a designated contact time), and whether it is applied as the only disinfection method in the local authority area. Two enquiries to this effect were sent to the relevant local authority, but no response was received.

3.3 Water company enquiries regarding public water supplies

Enquiries were sent out to 16 UK municipal water companies via WRc's Disinfection Forum regarding facilities where a public water supply is treated and distributed onsite (i.e. without any onward distribution). These may include a hospital or office/apartment block with an onsite water storage tank where the water receives some form of additional disinfection before being distributed onsite. Table 3.4 summarises water company responses on this topic.

Table 3.4 Water company responses regarding public water supplies

Water company	Examples of onsite disinfection of public water supplies
Northern Ireland Water	Two hospitals with dual borehole/municipal supplies, both treated for certain applications, e.g., renal/dialysis units. One has reverse osmosis, the other a multi-stage treatment plant. Factories that treat mains supply to obtain high purity water for their processes. Northern Ireland DWI (not water companies) are responsible for the Domestic Distribution Systems Regulations.
Southern Water	Company does not keep a record of buildings practising onsite disinfection of public water supply, though advise on water fittings compliance. Hospitals likely to treat/disinfect public water supply, though not to provide potable water.
Dŵr Cymru Welsh Water	Care home which installed hydrogen peroxide disinfection (at first unsuccessfully) for *Legionella* control. Company will respond to public water customers regarding enquiries made under the Water Supply (Water Fittings) Regulations 1999. Inspections of compliance failures at customers taps can reveal more details.
Wessex Water	Large care homes and hospitals "likely to have these systems", sometimes for *Legionella* control. Event reported to DWI in 2022 regarding taste and odour complaints from residents of an apartment block where chlorine dioxide disinfection of public water supply was applied.

These four water companies highlighted that care homes and hospitals, specifically are likely to practice additional onsite disinfection of public water supplies. Often this is for *Legionella* control or to provide high purity water for certain medical applications, such as dialysis. In terms of specific disinfection technologies, reverse osmosis, chlorine dioxide and hydrogen peroxide were noted. All these technologies are reviewed in Section 4, as they are also used for disinfection of private and municipal water supplies. There does not appear to be any technical or regulatory reason why disinfection technologies used for onsite disinfection of public water supplies would differ from those applied to other types of drinking water.

Table 3.4 suggests water companies are often only aware of onsite disinfection of public water supplies where the customer informs the company, or because compliance failures are investigated. These water companies report they do not necessarily keep a record of private treatment technologies installed, and are likely to have incomplete knowledge of the extent of relevant installations in their supply areas. While the examples provided in Table 3.4 result from customer complaints or problems with *Legionella* control, there is insufficient evidence to suggest that these occur more frequently as a result of disinfection of private water supplies.

4. Critical review of disinfection technologies used in England and Wales

4.1 Introduction

In this section, the 10 technologies selected in Section 3.2.5 are reviewed in terms of their capabilities as disinfectants, potential to generate disinfection byproducts and practical considerations, such as health and safety risks, operational costs and how straightforward they are to operate. Advantages and disadvantages of each technology were also collated and discussed.

Note that while 10 technologies are listed in Section 3.2.5, it was considered appropriate to group the three types of chlorination (hypochlorite solutions, OSE and chlorine gas) and two types of membrane technology (reserve osmosis and CCFs) for specific aspects in the remainder of this report.

In the context of public health, the efficacy of a disinfection technology is determined primarily by its ability to effectively reduce the concentration of microorganisms in drinking water to levels safe for human consumption. Because of the critical importance of this aspect of the performance of disinfectants, microbial efficacy is considered separately for all selected technologies in Section 4.2.

4.2 Microbial efficacy

Microbial removal efficacy was qualitatively assessed based on the capability of each disinfection technology to remove or inactivate three key microbial groups: bacteria, protozoa, and viruses. A brief overview of the evidence and relevant references identified to inform the assessment are summarised in Table 4.1, with the assessment findings presented in Table 4.2.

Table 4.1 Microbial removal efficacy – evidence and references

Disinfection technology									
	1-3. Chlorine (HOCl and OCl-), incorporating hypochlorite, OSE and chlorine gas	**4. Chlorine dioxide (ClO_2)**	**5. Chloramine (mainly NH_2Cl)**	**6. Ozone (O_3)**	**7. Hydrogen peroxide**	**8. UV irradiation**	**9. Reverse Osmosis (RO)**	**10. Ceramic candle filters (CCFs)**
Mechanism of action	Oxidation: Disruption of cell membrane/capsid proteins, DNA/RNA damage, inhibition of enzymatic acitivity[1,2,3]	Oxidation: Disruption of cell membrane/capsid proteins, DNA/RNA damage, inhibition of enzymatic acitivity[1,2,3]	Oxidation: Disruption of cell membrane/capsid proteins, inhibition of enzymatic activity[2,9]	Oxidation: Disruption of cell membrane/capsid proteins, DNA/RNA damage, inhibition of enzymatic activity[1,2,3]	Oxidation: Mechanisms not well understood; likely disruption of cell membrane, DNA/RNA damage[1]	Irreversible DNA/RNA damage[1,2,3]	Physical removal: mechanical filtration (pore size 0.0001-0.001 µm)[9]	Physical removal: gravity filtration (pore size 0.1-100 µm)[8]
Bacteria	Effective against most bacterial groups[1,6] Development of resistance is possible, with capacity for regrowth under low residual[1,7]	Effective against most bacterial groups[1,6]	Effective against most bacterial groups, but disinfection capacity is lesser than other oxidants[1,6]	Effective against most bacterial groups[1,6]	Effective against multiple bacterial groups inc. *Escherichia* and *Bacillus*[1] Effect on wider bacterial groups requires further study	Effective against most bacterial groups[1,5] Capacity for regrowth[1,7]	Effective removal of bacteria[9]	Effective removal of bacteria (dependent on pore size)[8] Silver coating improves efficacy[8]

	1-3. Chlorine (HOCl and OCl^-)	4. Chlorine dioxide (ClO_2)	5. Chloramine (mainly NH_2Cl)	6. Ozone (O_3)	7. Hydrogen peroxide	8. UV light	9. Reverse Osmosis (RO)	10. Ceramic candle filters (CCFs)
Protozoa	Some protozoan cell types e.g. *Cryptosporidium* oocysts are highly resistant[1,3,6]	Some protozoan cell types e.g. *Cryptosporidium* oocysts are highly resistant, though inactivation ability is greater than free chlorine[1,6]	Some protozoan cell types e.g. *Cryptosporidium* oocysts are highly resistant[1,3,6]	Effective against protozoa, including cysts and oocysts[1,6] Higher exposure may be required for inactivation[4]	Effective against certain groups e.g. *Cryptosporidium, Entamoeba* but research is minimal and effect of dif. cell types unclear[10] Resistance has been reported[11] Effect on wider protozoan groups requires further study	Effective against protozoa, including cysts and oocysts[1,5,6]	Effective removal of protozoa, including cysts and oocysts[9]	Effective removal of protozoa, including cysts and oocysts (dependent on pore size)[8]
Viruses	Widely effective against viruses[1,6]	Widely effective against viruses[1,6]	Effective against viruses, but disinfection capacity is lesser than other oxidants[1,6] Some viruses demonstrate resistance e.g. adenovirus, rotavirus[3,5,9]	Widely effective against viruses[1,6]	Effective against indicator viruses[1] Effect on wider viral groups requires further study	Widely effective against viruses[1,6] Some viruses demonstrate resistance e.g. adenovirus[5,9]	Effective removal of viruses[9]	Pore size too large to capture viruses[8] Silver coating has low affinity for viruses[8] Alternative coatings may improve removal[8]

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Table 4.2 Microbial removal efficacy – qualitative assessment findings

	Disinfection technology							
	1-3. Chlorine ($HOCl$ and OCl^-)	**4. Chlorine dioxide (ClO_2)**	**5. Chloramine (mainly NH_2Cl)**	**6. Ozone (O_3)**	**7. Hydrogen peroxide**	**8. UV light**	**9. Reverse Osmosis (RO)**	**10. Ceramic candle filters (CCFs)**
Bacteria	Excellent	Excellent	Good	Excellent	Good	Good	Excellent	Excellent to Fair
Protozoa	Fair to Poor	Good	Poor	Good	Fair	Excellent	Excellent	Excellent to Fair
Viruses	Excellent	Excellent	Fair	Excellent	Good	Good	Excellent	Poor

4.3 Chlorine

Chlorine is a widely used disinfectant, both in private and public supply. It is a strong oxidant which acts as a disinfectant by disruption of cell membrane/capsid proteins, DNA/RNA damage and inhibition of enzymatic activity (Table 4.1). It is widely understood to have excellent efficacy against bacteria and viruses and fair to poor efficacy against protozoa such as *Cryptosporidium* at accepted doses for drinking water (Table 4.2).

Chlorine is typically applied as a water disinfectant in one of four forms (Table 4.3, WHO, 2022):

- Chlorine gas
- Commercial sodium hypochlorite solution
- Onsite by electrolysis of brine to generate hypochlorite (OSE)
- Calcium hypochlorite powder, granules or tablets

Table 4.3 Types of chlorine used as drinking water disinfectants

Chlorine gas	Commercial sodium hypochlorite solution	Sodium hypochlorite solution, generated by onsite electrolysis (OSE)	Calcium hypochlorite powder, granules or tablets
• Manufactured by the electrolysis of brine. The gas is dried and then liquefied under pressure. • Often delivered in cylinders (33 kg or 71 kg Cl_2); drums (864 kg or 1000 kg Cl_2); or in tankers. • In this form, chlorine is essentially 100% active product, so when dosed to water no other substances are introduced. • A disadvantage is that if released to	• Sodium hypochlorite is produced by reacting chlorine with sodium hydroxide. It is supplied in solution at a maximum concentration *circa*.15% active chlorine. • During storage, hypochlorite degrades, primarily to chlorate and chloride.	• The principal components of an OSE system are salt saturator, an ion-exchange water softener and an electrolyser cell. • Bromate is a potential by-product • The most stable solutions are those of low hypochlorite concentration (< 10% active chlorine), with a pH of 11 and stored in the dark at a temperature below 20 °C.	• Calcium hypochlorite tablets contain about 65% active chlorine by weight. The tablets are stable if stored in sealed containers.

Chlorine gas	Commercial sodium hypochlorite solution	Sodium hypochlorite solution, generated by onsite electrolysis (OSE)	Calcium hypochlorite powder, granules or tablets
atmosphere, the chlorine will vaporise resulting in a highly toxic gas. • Bulk storage of 10 tonnes or more falls within the remit of the Control of Major Accident Hazards (COMAH) regulations. • Dosing equipment is designed to operate under a vacuum, to minimise risk of accidental leakage.	• Highly corrosive because sodium hydroxide is added to raise pH and slow degradation. • Degradation increases at higher temperatures, higher initial concentrations, and under UV light.		

4.3.1 Chlorination disinfection byproducts (DBPs)

Chlorination DBPs include a wide variety of halogenated and non-halogenated organic compounds, notably trihalomethanes (THMs) and haloacetic acids (HAAs). Both of these groups form through the reaction of chlorine with natural organic matter (NOM; (Bond et al.et al., 2020). Chlorinated, as well as brominated, forms can result, the exact proportions controlled by the concentration of bromide in the influent. Mechanistically, free chlorine oxidises bromide to produce bromine which can react with organic and inorganic impurities (Premarathna et al.et al., 2023). If the bromide concentration is low in influent water, then the wholly chlorinated THM (chloroform) will typically predominate over other THMs. At intermediate bromide levels the mixed chlorinated/brominated THMs (dibromochloromethane and bromodichloromethane) typically predominate and at very high bromide levels the wholly brominated THM (bromoform) will predominate. This pattern also applies to other halogenated DBPs such as the HAAs. Bromoform is considerably more toxic than chloroform (Villanueva et al.et al., 2023). There are many other halogenated species formed during chlorination, but these are so far unregulated. These include haloaldehydes, haloketones, haloacetonitriles, haloacetamides and halofurans (Kali et al.et al., 2021).

Less than 10% of total chlorine is consumed in the formation of halogenated byproducts and the majority of non-halogenated byproducts which are produced are currently unregulated (AWWA, 1999; Lei et al.et al., 2023). Recent research has identified a number of non-halogenated DBPs which pose potential risks to health. For example, N-nitrosamines have been classified as probable carcinogens (Lei .et al., 2023).

Organic DBPs contribute to dissolved organic carbon, which can promote the formation of biofilms throughout the distribution system even when residual disinfectant is present (AWWA, 1999; Tsagkari and Sloan, 2023).

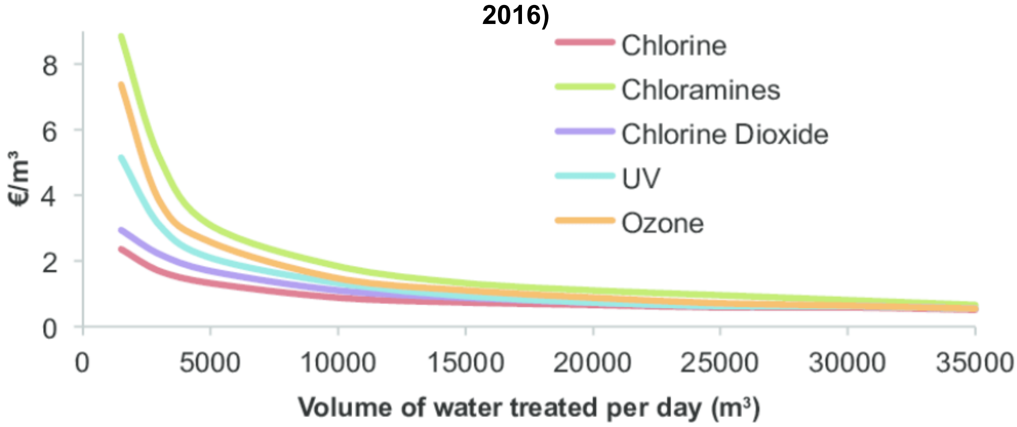
4.3.2 Practical considerations

The use of chlorine gas poses several major risks associated with safe handling. Due to its toxicity and high oxidation potential, specialised training, protective equipment, and facilities are required (Choi et al.et al., 2021). To avoid these handling hazards, either aqueous sodium or calcium hypochlorite can be substituted as a source of active chlorine for disinfection.

Sodium hypochlorite can either be purchased from an approved supplier or generated on site via the electrolysis of brine to produce chlorine and sodium hydroxide which react to form sodium hypochlorite (Afify et al.et al., 2023). The use of commercially available sodium hypochlorite solution still requires careful storage to prevent exposure to sunlight and heat. Otherwise, it can degrade to form toxic inorganic contaminants including chlorate and perchlorate (Choi et al.et al., 2021). Furthermore, chlorate, chlorite and bromate can be present as impurities in hypochlorite solutions (Asami et al.et al., 2009). On-site electrolysis generated chlorine is relatively safe, and the generation process requires less specialised facilities and training. Additionally, lower transportation costs are incurred for the delivery of inert feedstock chemicals (Choi et al.et al., 2021).

Chlorination is often considered more cost-effective than other disinfection technologies (chloramines, chlorine dioxide, UV and ozone) across a range of flows (Fitzhenry *et al.*, 2016). For chlorination, as with other disinfection methods in this review, economies of scale account for lower costs at higher treatment volume (Khaleghi Moghadam and Dore, 2012).

Figure 4.1 Cost comparison of key disinfection technologies (Fitzhenry *et al.*, 2016)



Due to competing industrial uses for the chemicals required, chemical costs are subject to fluctuation and can impact operational costs (SEPA, 2022). With these supply issues in mind, while the initial investment for on-site generation of hypochlorite may be higher, operational costs are reduced when compared to chlorine gas systems (Ozel Celik et al.et al., 2017)

4.4 Chlorine dioxide

Chlorine dioxide is a stronger oxidant than chlorine and is widely accepted to be a more effective disinfectant (USEPA, 1999). Chlorine dioxide gas is unstable, and explosive under pressure, so is generated on-site, most commonly from electrochemical methods involving sodium chlorite and either acid or chlorine (WRc, 2019).

An alternative chemical approach is the reduction of sodium chlorate using hydrogen peroxide and sulphuric acid.

Chlorine dioxide acts as a disinfectant by oxidative disruption of cell membrane/capsid proteins, DNA/RNA damage and inhibition of enzymatic activity (Table 4.1). It is considered to have excellent efficacy against bacteria and viruses and good efficacy against protozoa (Table 4.2).

Advantages of chlorine dioxide as a disinfectant (USEPA, 1999; EPA, 2011) include:

- Biocidal properties which are insensitive to pH over the range pH 6-9.
- When dissolved it does not dissociate, which is beneficial for penetrating biofilms.
- Does not undergo chlorine-substitution reactions, so does not itself produce disinfection by-products (DBPs), such as THMs and HAAs.
- Does not react with ammonia, so no risk of problematic taste and odour from di- or tri-chloramines as can occur during chlorination.

Disadvantages include:

- Decomposes to form chlorite and chlorate, which are toxic DBPs.
- Needs to be generated on-site. Process can include chlorine gas or sodium hypochlorite solution, which can result in some THM and HAA formation if not optimised.
- May cause taste and odour problems if residual is ≥ 0.2 mg/L. Readily volatilizes so can cause chlorinous odour at customers' taps; also some evidence of reacting with volatile organic compounds (VOCs) in customers' homes, resulting in other odours.

4.4.1 Chlorine dioxide disinfection byproducts

Chlorine dioxide reacts with natural organic matter (NOM) to form a wide range of oxidised organic molecules, including aldehydes, ketones and acids (AWWA, 1999). Alongside these, chlorite (ClO_2^-) and chlorate (ClO_3^-) ions are formed from decomposition of chlorine dioxide (Al-Otoum et al.et al., 2016). These ionic species - as well as the chlorine dioxide itself - are considered to have adverse health impacts and must be below approved levels in finished waters (DWI, 2023). The sum of all three species must not exceed 0.5 mg/L (DWI, 2023).

The production of halo organics such as HAAs and THMs is negligible when using chlorine dioxide as a disinfectant and so the chlorine containing species listed above are of high concern from a regulatory perspective. Where higher disinfection efficiency and lower byproduct formation is required, chlorine dioxide is often preferred over chlorination with free chlorine (Wang et al.et al., 2024). However, the cost of chlorine dioxide treatment is significantly higher than disinfection using sources of free chlorine (Gonce, 1994).

A combination of chemical disinfection methods can reduce the production of regulated DBPs. For example, using chlorine dioxide treatment as a primary disinfection step followed by chlorination with a source of free chlorine can alter the structure of certain NOMs and therefore reduce the formation of regulated DBPs such as THMs and HAAs (Valenti-Quiroga et al.et al., 2024). However, alongside the benefits associated with the implementation of multiple chemical disinfection steps, this does increase complexity and perhaps the costs of treatment.

4.4.2 Practical considerations

Chlorine dioxide dosing systems typically blend solutions of sodium chlorite and hydrochloric acid to produce chlorine dioxide. Continuous dosing systems are most common and so storage for chlorine dioxide is not needed. Systems such as the Feedwater Activ-Ox® are completely automated and require limited expertise for operation. This type of dosing equipment includes two precision dosing pumps, a control system with interface, and a pair of bunded storage tanks for the feedstock chemicals.

Most chlorine dioxide units use hydrochloric acid as one of the feedstock chemicals, typically at 9% strength, which requires careful handling (WRc, 2019). If improper storage leads to contact with the other feedstock chemical, there is a risk of chlorine dioxide gas being generated. As mentioned, chlorine dioxide gas is highly unstable and while not inherently combustible, can react violently with organics, phosphorus, potassium hydroxide and sulphur, posing a fire and explosion hazard (Public Health England, 2016).

4.5 Chloramines

Formed in situ through the reaction of chlorine and ammonia, chloramines (comprising monochloramine, dichloramine and trichloramine) are less powerful disinfectants than free chlorine but are more stable through the distribution system and thus provide a persistent chlorine residual (AWWA, 1999). Under typical water treatment conditions monochloramine is the predominant species. The weaker disinfection capability of chloramines is reflected in a reduced microbial removal efficiency in comparison to other oxidants, with good removal of bacteria, fair removal of viruses, and poor removal of protozoa (Table 4.2). Notably, several types of virus (adenovirus, rotavirus) and protozoa (*Cryptosporidium*) have demonstrated resistance to chloramine disinfection (Table 4.1).

Typically, the dose ratio of chlorine to ammonia ranges from 5:1 to 7:1 as a weight ratio of Cl_2:NH_3-N (Brandt et al.et al., 2009a). Monochloramine is the desired product of chloramination, firstly because it has the greatest biocidal effect and secondly because the other two species can cause taste and odour complaints (CIWEM, 2017). Limited amounts of chloramines will be produced during the other chlorination methods described due to reactions with naturally occurring ammonia (Brandt et al.et al., 2009a).

Disinfection with chloramines works through disruption of cell membranes/capsid proteins (Table 4.1).

Advantages of this technology (USEPA, 2009) include:

- Chloramines provide long lasting residual for large distribution networks.
- Chloramines do not react with organic matter to produce DBP to the same extent as free chlorine.
- Chloramines react less with NOM and therefore produce lower concentrations of DBPs.

Disadvantages include:

- Lower biocidal efficacy than free chlorine disinfection.
- Nitrification can occur through the bacterial oxidation of chloramine decay products

4.5.1 Chloramine disinfection byproducts

Because of the lower reactivity of chloramines, they tend to produce much lower concentrations of the typical chlorination DBPs such as THMs and HAAs (AWWA, 1999). However, it is worth noting that small amounts of free chlorine present during or after chloramination contribute to formation of such byproducts. Cyanogen chloride and nitrosamines, notably N-Nitrosodimethylamine (NDMA) are reported to be true chloramination DBPs, with concentrations generally higher in systems using chloramination than chlorination (AWWA, 1999).

While there is no current regulatory standard in England and Wales for NDMA in drinking water, it is classed as a possible carcinogen (WRc, 2008). Chloramines decompose to produce ammonia which can be oxidised to nitrite and nitrate by nitrifying bacteria. Therefore, there is potential for increased concentrations of nitrite in chloraminated systems (Shi et al.et al., 2020), which is regulated by the DWI.

Chloronitramide anion ($Cl\text{-}N\text{-}NO_2^-$), a previously unidentified by-product resulting from inorganic chloramine decomposition, has been detected in chloraminated US drinking water, with median concentrations of 23 µg/L (Fairey *et al.*, 2024). Further study is required to understand the toxicity of this compound.

4.5.2 Practical considerations

Chloramination can be achieved through the simultaneous addition of chlorine and ammonia or through the addition of ammonia either before or after chlorination. The specific addition order can impact the formation of DBPs and the eventual biocidal power of the chloramine residuals generated (AWWA, 1999).

While chloramines residuals provide significantly less biocidal efficacy, they are also more stable in a distribution system than free chlorine. Common practice in the UK is to complete primary disinfection at the treatment works using the more powerful free chlorine disinfectant. Chloramination is then completed to maintain a chloramine residual in the distribution system (CIWEM, 2017).

Chloramines react with lead to produce more soluble oxidation products than when free chlorine is used. There are also concerns that toxic lead oxidation products can leach into supplied water in chloraminated distribution systems (CREW, 2012).

Additionally, blending of chloraminated water with water containing free residual chlorine in distribution systems could result in the formation of dichloramine and nitrogen trichloride, which can lead to taste complaints (Brandt et al.et al., 2009b).

4.6 Ozone

Ozone is a stronger oxidant than either chlorine or chlorine dioxide and is reported to be a more effective disinfectant for inactivation of viruses and protozoa (USEPA, 1999a).

Ozone is an unstable gas which must be generated on demand at the point of use (USEPA, 1999a). Generation is by corona discharge of dried air or oxygen. Using oxygen avoids the requirement to dry air and produces a higher concentration of ozone from a lower energy input; but entails the cost of purchasing liquid oxygen, or on-site oxygen separation from air (AWWA, 1999).

The conventional approach of dissolving ozone is by mounting diffusers (either of sintered construction, or membranes) on the base of vertically baffled concrete tanks of approximately five metres depth, with gas bubbles of approximately two millimetres rising either counter-currently or co-currently with the water flow (WRc, 2019). Alternatively, a pipe reactor may be used, into which the ozone gas might be injected directly, upstream of a static mixer, or applied via an eductor in a side stream. Off-gas from the contactor normally requires treatment (thermal or catalytic) before venting to atmosphere, to destroy any ozone which has not dissolved (WRc, 2019).

Ozone has not been adopted in the UK for primary disinfection of public water supplies, though it is used as an oxidant in the UK and as a disinfectant elsewhere in Europe and in America (WRc, 2019).

Ozone acts as a disinfectant by disruption of cell membrane/capsid proteins, DNA/RNA damage and inhibition of enzymatic activity (Table 4.1). It is considered to have excellent efficacy against bacteria and viruses and good efficacy against protozoa (Table 4.2).

According to USEPA (1999) and EPA (2011) the advantages of ozone include:

- Biocidal properties which are insensitive to pH over the range pH 6-9.
- Requires a short contact time, compared with free chlorine.
- Avoids formation of chlorine-substituted DBPs such as THMs and HAAs.
- Decomposes to oxygen.

Disadvantages are listed as

- Oxidises bromide to bromate, which is a regulated DBP.
- In the presence of bromide, additional brominated DBPs can be formed.
- Reacts with organic matter, producing DBPs such as aldehydes and ketones and generally increasing biodegradability as measured by determinands such as assimilable organic carbon. Consequently, biologically active filters (usually Granular Activated Carbon (GAC)) are typically applied downstream of ozonation.
- Rapidly decomposes, so does not provide a residual.
- High capital and operating costs.
- Leakage of ozone gas represents a health and safety risk

4.6.1 Ozonation disinfection byproducts

As with other oxidants, the formation of DBPs during ozonation is unavoidable. Alongside several organic DBPs, ozonation can lead to the formation of bromate at high doses and high influent bromide concentration (de Carvalho Costa et al.et al., 2024). Initial oxidation of bromide produces hypobromous acid which further oxidises to bromate. The hypobromous acid reacts with NOM to form a range of brominated organics including THMs and HAAs (Wen et al.et al., 2018). Bromate poses known risks to human health and is regulated at 10 µg/L in UK drinking water. Therefore, ozonation is often unfavoured for treatment of source waters with high bromide concentrations (AWWA, 1999).

The pH of influent water plays an important role in the formation of bromate, with higher pH leading to the formation of higher concentrations (Morrison et al.et al., 2023). Even though halogenated DBPs are a concern, the majority of DBPs from ozonation are less-harmful aliphatic and aromatic compounds (Laflamme et al.et al., 2020). Some of these compounds are produced to a similar degree as with other disinfection processes - such as chlorination - and are subject to increasing scrutiny as more is discovered about their toxicity (Laflamme et al.et al., 2020). Conversely, other studies suggest that ozonation produces higher levels of ketone and aldehyde byproducts (AWWA, 1999).

4.6.2 Practical considerations

Several components comprise an ozone gas disinfection system. These include the gas generator itself alongside a contactor, an ozone destructor to treat off-gas, and an ozone gas monitor to detect leaks (USEPA, 1999a). Specific training is required for operators due to the complexity of these systems. Ozone leakage can pose risks to operators by exacerbating any respiratory problems, highlighting the health and safety concerns associated with this technology (USEPA, 1999a; Li et al.et al., 2019).

Ozone disinfection is generally more expensive than both chlorination and UV treatments, in capital cost as well as operational and maintenance costs (USEPA, 1999a). Operation and maintenance are also complex compared with liquid disinfectant technologies.

4.7 Hydrogen Peroxide (H_2O_2)

Hydrogen peroxide (H_2O_2) is a potent oxidising agent and effective disinfection process for the inactivation of a range of microorganisms, acting through both intra and extracellular routes to interrupt cellular function (Silva, 2022). However, there are few examples of H_2O_2 being used as a standalone treatment for potable water disinfection. Rather, it is more commonly used in conjunction with UV radiation in advanced oxidation processes (Bilal et al.et al., 2022). Examples of H_2O_2 use are largely isolated to *Legionella* control (Stavrou et al.et al., 2020).

The lack of wide-spread use and relevant research makes implementation challenging because required dose and inactivation kinetics are unknown across varying influent conditions. Furthermore, information regarding toxicity and residual disinfection are lacking. H_2O_2 is reported to be more environmentally-sustainable than chlorine because it produces significantly lower levels of halogenated DBPs and instead decomposes into water and hydrogen (Kamila Jessie Sammarro Silva, 2022).

The mechanisms of disinfection are not well understood for hydrogen peroxide but, as an oxidant, it is likely that disruption of cell membrane/capsid protein and genomic damage are key in microbial inactivation (Table 4.1). It has shown to have good disinfection efficacy for bacteria and viruses, and fair efficacy for protozoa, though it is important to note that considerably less evidence is available for this disinfection method compared to others (Table 4.2**).** This project recommends that further study is needed to fully understand the efficiency of H_2O_2 against wider bacterial, viral, and protozoan groups.

Potential advantages of hydrogen peroxide as a disinfectant (ChemREADY, 2025) are:

- Effective against protozoa
- Broad spectrum disinfection of bacteria, viruses and fungi
- Decomposes into water and oxygen making it environmentally friendly

Potential disadvantages of hydrogen peroxide as a disinfectant (ChemREADY, 2025) are:

- Decomposes in sunlight making correct storage essential
- Poses handling risks as it is an irritant
- Has uncertain short-lived residual (Clark et al.et al., 2009; Wang et al.et al., 2017).
- Disinfection efficacy less well understood than other selected chemical disinfectants

4.7.1 Practical considerations

It is difficult to comment in detail on the practical aspects of disinfection using H_2O_2 due to the limited available literature. Small scale applications for legionella control are more common than for large scale water treatment (ChemREADY, 2025; Girolamini et al.et al., 2019). A disadvantage of using H_2O_2 is that its potency is influenced by several factors including pH and temperature which must be accounted for during disinfection and therefore increases complexity (Girolamini et al.et al., 2019).

4.8 UV irradiation

UV irradiation is a non-chemical means of disinfecting water. Essentially, UV light transmitted into a water column is absorbed by the nucleic acids and proteins of microorganisms (Kim et al.et al., 2023). The energy from the photons absorbed by the organism cause damage which reduces the ability to replicate and perform key cellular functions required for infection (Table 4.1, Kim *et al.*, 2023). Because a UV-inactivated organism is not destroyed completely, some degree of genetic or enzymatic repair can occur. This is more common in instances where insufficient UV dose is applied (AWWA, 1999). However, it has been shown that combination with chlorination can minimise the efficacy of these repair mechanisms (Linden et al.et al., 2019).

Through damage to genomic material and proteins (Table 4.1), UV germicidal radiation displays good efficacy for bacteria and viruses, and excellent efficacy for protozoa (Table 4.2).

Advantages of this technology include:

- Effective against bacteria, viruses, and protozoa

- Germicidal effectiveness for standard bacterial and viral indicator organisms is representative of actual microorganism inactivation
- No known toxic by-products formed, although nitrite may be formed under certain circumstances.
- Low operation and maintenance costs
- Small footprint
- Short contact times

Disadvantages of this technology include:

- No residual disinfectant
- Limited efficacy against adenoviruses
- Complexity measuring effective germicidal UV dose
- Potential for microbial reactivation and biofilm formation
- Lamp fouling
- High demand for electricity, compared with other disinfectant technologies

4.8.1 UV-induced disinfection byproducts

Another factor in the rapidly increasing interest in UV disinfection of water is it does not negatively affect the formation of halogenated disinfection by-products (DBPs) or other byproducts such as bromate (AWWA, 1999). UV light itself does not contribute to the formation of regulated DBPs, although DBP precursors will form at doses in excess of that typically used for disinfection of drinking water (Zhao et al.et al., 2021). Small changes in natural organic matter (NOM) structure have been reported but no effects on THMs and HAAs were noted (Gallard and von Gunten, 2002; Paul et al.et al., 2012).

Photolysis of nitrate to nitrite is one area of potential concern (Lu et al.et al., 2009). Nitrate may be present in groundwaters and some surface waters and absorbs UV light below 240 nm, in the output range of medium pressure (MP) UV sources but not low pressure (LP) sources. The formation of nitrite is complex and may be influenced by the presence of organic matter and pH, but when nitrate is below the regulated maximum contaminant limit (MCL; USEPA), there is minimal chance that nitrite formation would occur at levels above the USEPA-regulated limits, although the DWI limits are stricter at 0.5 $mg \cdot NO_2L^{-1}$ (Sharpless and Linden, 2001). The UV doses typically applied in water treatment may result in the formation of nitrogenous DBPs such as chloropicrin. Although not thought to be generated in significant quantities, their formation mechanisms are incompletely understood (Reckhow et al.et al., 2010).

4.8.2 Practical considerations

Studies have reported that UV systems can be cost competitive with chlorination at high treatment capacities. These costs will likely continue to fall as lamp technology and system design improves (Mohamad Mazuki et al.et al., 2020). For chemical disinfection, the highest cost is often incurred by the need to purchase feedstock chemicals whereas the greatest cost for UV is the high energy demand (USEPA, 1999b). The operating and maintenance costs for UV are reported to be significantly lower than for chlorination as chemicals are not required in such abundance, especially when a dechlorination step is required (Tak and Kumar, 2017).

Energy demands are the main contributor to the operational cost of UV disinfection. Appropriately designed UV disinfection systems typically use less than 20 kWh/ML of energy, which is less than or equivalent to ozonation when compared for the same treatment objective (CIWEM, 2019).

UV reactor operators must complete a regime of checks to ensure effective disinfection and to comply with regulations. These include the monitoring of flow rate, turbidity, UV fluence rate and lamp condition. Turbidity can greatly reduce the transmittance of UV radiation through water and hence reduce the impact on microorganisms (Farrell et al.et al., 2018). Regular cleaning and inspection of UV lamps is essential to prevent lamp fouling from reducing disinfection power (DWI, 2016).

Biodosimetry is the main method by which UV reactors are validated for efficacy against microbes, both pre-installation and during operation (Qiang et al.et al., 2013). A target microorganism is spiked into the influent water and then inactivation is measured post treatment. A UV inactivation curve produced through bench scale analysis is then used to determine the ‘effective fluence’ delivered by the reactor. This is a useful approach because it demonstrates the efficacy of the reactor under real operating conditions. However, biodosimetry is a relatively expensive and time-consuming process and so on-site measurements under representative conditions are often limited (Qiang et al.et al., 2013).

4.9 Membrane technologies

4.9.1 Reverse Osmosis (RO)

Reverse Osmosis (RO) has been implemented for a range of water treatment needs including the production of drinking water from low quality raw waters. RO systems can be used to treat a range of physically and chemically diverse substances including dissolved inorganic species (e.g. sodium, calcium, nitrate and fluoride) and organic pollutants including pesticides and solvents. RO can also produce microorganism-free water (DWI, 2009).

Water is forced through a semi-permeable membrane under high pressure which imposes higher energy requirements than gravity fed filter systems. Some degree of pretreatment is typically required to prevent excessive fouling. Lower pressures are applied in RO systems for private water supply compared with municipal treatment works. Therefore they produce a slower flow rate and require holding tanks for treated water to act as a buffer when demand is high. Periodic disinfection of the holding tank is recommended. There is evidence that inadequate cleaning of the storage system and pipework associated with RO units can result in proliferation of bacteria that are of health significance (DWI, 2009).

Advantages (Tayeh, 2024) are that RO:

- Effectively removes a range of chemical and physical contaminants
- Effectively removes bacteria, viruses and protozoa

Disadvantages may include:

- A large volume of wastewater is produced
- Demineralisation can lead to corrosion of metal fittings
- Energy costs imposed through need for pressurisation of influent
- Low throughput rate
- Pre-treatment generally required

4.9.2 Ceramic candle filters (CCFs)

Often used in less economically developed settings due to the low capital and operational costs, CCFs and other similar filters have found a market in private water supplies in England and Wales. Comprised of a porous ceramic material, these filters physically remove impurities such as dirt and microorganisms based on their inability to pass through small pores (DWQR, no date). Filter fouling can occur when concentrations of dissolved impurities are high and therefore some degree of maintenance is required. Because these filters operate under gravity, energy requirements are exceptionally low. However, application of pressure can massively increase treatment capacity (DWI, 2009).

This technology is often used in municipal water production as a pretreatment step to improve the disinfection efficiency of subsequent processes affected by turbidity and organic contamination, rather than as a sole disinfectant. Studies have shown CCF to be effective for the removal of *Cryptosporidium*, bacteria and a range of viral indicators (Adeyemo et al., 2015). A potential drawback is that the high mineral content of hard water can precipitate and eventually block the filter (DWI, 2009). Also, bacterial growth within the filter can lead to contamination of treated water. Regular filter changes and flushes are required, and certain brands incorporate a silver coating to inhibit bacterial growth.

Advantages include (DWI, no date):

- Low capital and operational costs
- Limited expertise required to set up and operate
- No chemical risk

Disadvantages include:

- No residual disinfection
- Bacterial growth can lead to contamination of treated water
- Prone to blockage

4.9.3 Practical considerations for all membrane processes

CCFs, RO and micro, nano or ultra-filtration technologies can be considered as a group in practical application. These provide disinfection through similar principles but with differing porosity (Youmoue et al.et al., 2017).

Fouling of membranes is common and can be caused by inorganic matter or biofouling, whereby biological growth can block pores and reduce treatment capacity (Armstrong *et al.*, 2011). Fouling is one of the most important factors that has limited the use of membrane technology for the removal of microorganisms from water (Madaeni, 1999). The use of biocides to control biofouling is common, although the bacteria in biofilm can be resistant to these agents. In addition, biocides produce an accumulated biomass which encourages active re-growth (Armstrong *et al.*, 2011).

Because RO removes much of the mineral content from treated water, there is likely to be increased corrosion of metallic fittings. Therefore, remineralisation is recommended to prevent the leaching and subsequent ingestion of metals (Shrestha and Li, 2017). A further disadvantage is that a relatively high volume of water is wasted. The requirement for high pressure in larger systems significantly increases costs through energy demand and can make RO less attractive when compared to conventional disinfection methods (Skoronski et al.et al., 2024). Compared to RO, other membrane processes with larger pore size can operate under lower pressures and are therefore more cost effective due to their lower energy requirements (Hu et al.et al., 2024).

During production of drinking water, relatively large volumes of reject water are generated. Therefore, RO is often considered as a last resort treatment for production of drinking water from sources with unfavourable chemical profiles, such as brackish water, or selected for situations in which the purest water is required (DWI, 2009).

The physical removal of different microorganisms depends on the specific pore size of the membrane used, with the smallest pore sizes used in RO (0.001-0.0001 µm) providing excellent removal efficacy for bacteria, protozoa and viruses (Table 4.2). The larger pore sizes in CCFs (0.1-100 µm) provide poor efficacy for viruses but good to excellent efficacy for bacteria and protozoa, depending on specific pore size (Table 4.2).

4.10 Overview comparison

A summary of the aspects discussed in Section 2 of this report can be found in Table 4.4. This summary is largely adapted from a report produced by the Environmental Protection agency of Ireland (Fitzhenry *et al.*, 2016)

Table 4.4 Qualitative summary of practical aspects for selected disinfectants. Adapted from Fitzhenry et al.et al., 2016; Collivignarelli et al.et al., 2017.

	Chlorine gas	Hypochlorite	Chlorine dioxide	Chloramination	Ozone	UV radiation	Membrane technologies
Equipment reliability	High	High	High	High	High	Medium	Medium
Technology complexity	Low	Low/Medium	Medium	Low	Medium	Medium	Low
Health and safety considerations	High	Low	High	Medium	Medium	Low	Low
DBP formation	High	High	Medium	Medium	Medium	Low	Low
Ease of asset management	High	High	Medium	Medium	Low	Medium	Low/High
Operational cost	Low	Low	Medium	Low/Medium	High	Medium	Low/High

5. Multi criteria analysis of disinfection technologies used in England and Wales

5.1 Methodology

The information gathered in Section 4 regarding the performance, advantages and limitations of each technology has been used to conduct a multi criteria analysis (MCA). This enables simplified comparison between the different technologies in the context of the disinfection of public and private water supplies.

MCA (also called multi criteria decision analysis) is an analytical method used to rank a set of options assessed against a range of criteria or performance objectives. MCA simplifies decision-making by providing a structured framework for ranking options based on multiple criteria. This approach is particularly useful for decision-makers who prioritise sensitivity to specific criteria over others, as the weightings of selected criteria can be varied by the user. In this way, it allows for nuanced comparisons and informed choices.

MCA processes may vary slightly depending on the specific case. However, the process outlined in Table 5.1 was identified as the most suitable for this project, and comprise the following steps:

Step 1: Select disinfection technologies (completed in Section 3.2.5)

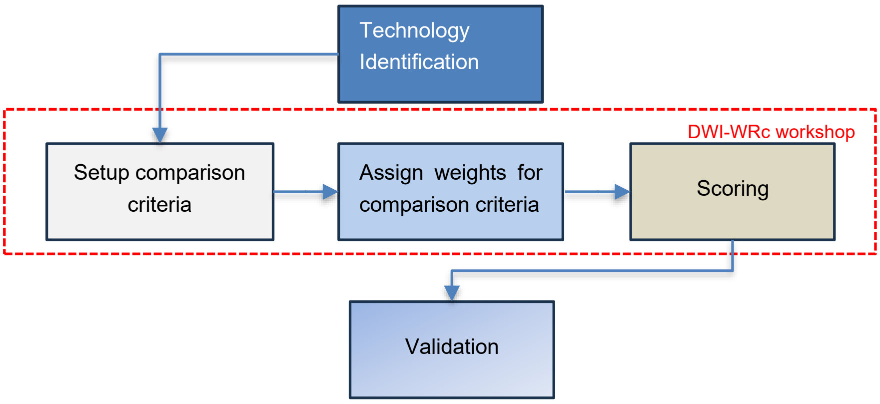
Step 2: Select relevant criteria for ranking

Step 3: Assign relative weights to the criteria

Step 4: Score the performance of technologies against each criterion

Step 5: Consolidate and summarise scores and sense check

Figure 5.1 MCA process schematic



5.1.1 Step 1: Select disinfection technologies

The ten technologies listed in Section 3.2.5 and reviewed in Section 4 will be ranked using MCA during this section of the report.

5.1.2 Step 2: Identify relevant criteria for ranking

The second step was to identify a set of performance criteria against which each technology can be compared. A few important points should be considered when defining the criteria:

- Criteria should be measurable, either qualitatively or quantitatively, based on how the options perform. For example, this might involve using a measurable scale, a constructed scale, or a pairwise comparison.
- Criteria should be mutually independent, with no causal relationship where performance on one criterion directly influences performance on another.
- Qualitative criteria should be defined precisely to make scoring each technology easier and more effective.

Six criteria (Table 5.1) were selected for inclusion following discussion between WRc and DWI: operational cost, ease of asset management, DBPs, efficacy against microorganisms (split into three sub-criteria, relating to bacteria, protozoa and viruses), footprint and health and safety.

5.1.3 Step 3: Assign relative weights to the criteria

The individual performance scales for each criterion cannot be directly combined because a unit on one scale does not necessarily correspond to a unit on another. Therefore, it is essential to derive weightings for the criteria, taking into account the relative difference between the best and worst-performing options for each criterion, as well as the importance of each criterion in relation to the desired outcome. Weighting methods include:

1. Weighted Sum Method: The weightings are assigned such that they total 1 (or 100). Each criterion receives a portion based on its relative importance and significance to the desired outcome.
2. Randomised Weighting Method: In this approach, weights are assigned using values typically centred around 1, adjusted up or down depending on the perceived effect of each criterion. For example, criteria with higher importance might be assigned weights above 1, while less impactful criteria are assigned weights slightly below 1. This method provides a flexible starting point and can be refined based on participant feedback or further analysis.
3. Rank-Based Weighting: The criteria are ranked from most important to least important. Weights are then calculated based on the rank order. However, this method has limitations, as it does not allow for assigning equal weights to two or more criteria, and the difference between the highest-ranked and lowest-ranked criteria can become large when the list of criteria is long.

The first method was selected to assign weightings, the weighted sum method is straightforward and ensures balanced weight distribution. Since the sum must always equal 1, it facilitates comparison across multiple alternatives.

5.1.4 Step 4: Score the performance of technologies against each criterion

The next step involved inviting participants to assess the performance of each technology with respect to the defined criteria. This was undertaken by WRc staff utilising information gathered from literature reviews and expert judgment. Scoring results were then reviewed and validated in an internal workshop.

Quantitative data associated with a criterion are generally straightforward to score. The analysis of quantitative performance data was outside the scope of this project. For qualitative or semi-quantitative data a numerical scale can be created by identifying the least-performing and most-preferred technologies. The highest score (in this case, 5) is assigned to the best-performing technology and the lowest score (1) to the worst-performing. All other technologies are then evaluated and scored relative to these benchmarks.

5.1.5 Step 5: consolidate and summarise scores and sense check

At this stage, the assigned scores and weightings are reviewed and validated. This process does not necessarily need to be carried out by the same group that conducted the initial scoring; indeed, it often involves external experts or a broader group of stakeholders. This step includes verifying the logic behind the scoring, checking for potential biases, and confirming that the weightings appropriately reflect the relative importance of the criteria.

In this instance, the outputs of the MCA were validated and adjusted during a project workshop involving WRc and DWI to ensure outcomes aligned with project objectives, criteria were applied consistently and judgements based on sound scientific information.

5.2 Multi criteria analysis results

As a result of the validation workshop, involving WRc and DWI, the 'scalability' criterion was removed because it was agreed that assigning a score would depend significantly on site-specific circumstances, making it difficult to generalise across multiple sites. Also the weighting applied for 'Microbial efficacy' was increased, reflecting its critical importance to public health.

Table 5.1 presents these revised evaluation criteria, their respective weighting, and the justification. Microbial efficacy has highest weighting of 0.45 (0.15 for each sub-criterion), followed by operational cost (0.2) and ease of asset management (0.2). DBPs, footprint, and health and safety were given weightings of 0.05 each.

Table 5.1 Details of selected MCA criteria

ID	Criteria	Description	Criteria type	Weight	Justification
C1	Operational cost	The cost associated with operation of the technology, e.g., energy and chemical consumption	Qualitative or semi-quantitative	0.2	Impacts technology uptake and potentially long-term efficacy (e.g., if maintenance requirements are not followed)
C2	Ease of asset management	The complexity of operating the disinfection technology and maintenance requirements. Longevity, ease of verification	Qualitative or semi-quantitative	0.2	Impacts the long-term efficacy and public health impact of the technology
C3	DBPs	The quantity and likelihood of disinfection by-product (DBP) formation	Qualitative or semi-quantitative	0.05	DBPs are important, but health risk from likely levels of exposure less than microbiological water quality.
C4 (i)	Efficacy against bacteria	Bacteria load reduction	Qualitative or semi-quantitative	0.150	Critical in terms of public health
C4 (ii)	Efficacy against protozoa	Protozoa load reduction	Qualitative or semi-quantitative	0.150	Critical in terms of public health
C4 (iii)	Efficacy against viruses	Virus load reduction	Qualitative or semi-quantitative	0.150	Critical in terms of public health

ID	Criteria	Description	Criteria type	Weight	Justification
C5	Footprint	The space occupied by the technology	Qualitative or semi-quantitative	0.05	Considered less critical than other criteria
C6	Health and Safety	The level of risk associated with handling and using disinfection technology	Qualitative or semi-quantitative	0.05	Safety of the operators and public is paramount. However, risks are managed through proper H&S protocols.

Table 5.2 defines the scores for each criterion. A score of 5 indicates the best performance, while a score of 1 denotes the worst.

Table 5.3 presents the MCA scores and final output of the weighing exercise.

Table 5.2 Definition of scores for each criterion

ID	Criteria title	5	4	3	2	1
C1	Operational cost	Very low operational costs	Low operational costs	Moderate operational costs	High operational costs	Very high operational costs,
C2	Ease of asset management	Very easy – Fully automated system which requires no operational time	Easy – Simple to operate with minimal supervision or training	Moderately easy – Some user-friendly features but still requires expert intervention	Complex – Moderate to high training required to operate the systems	Very complex – Requires extensive expertise, very high training and a significant effort to manage the systems
C3	DBPs	Negligible Risk – Produce no DBPs or effectively removes existing DBPs	Low – Produces minimal DBPs or has effective systems for their removal	Moderate – Produces a noticeable amount of DBPs, but mitigation strategies are moderately effective	High – Produces high level of DBPs, and removal is difficult	Very high – Produces significant harmful DBPs with no ability to mitigate or remove them
C4	Microbiological efficacy C4 (i) Bacteria	Excellent – High microbial inactivation rates, meeting regulatory standards Consistent performance under real world conditions	Very good – Significant microbial load reduction - meeting regulatory standards	Good – Moderate microbial reduction achieved under controlled conditions. Optimisation required - meeting regulatory standards	Fair – Some microbial reduction is observed but not consistent across different water conditions. Requires additional treatment steps to meet drinking water standards	Poor – The disinfection method shows little to no reduction in microbial load.
	C4 (ii) Protozoa					
	C4 (iii) Viruses					
C5	Footprint	Very compact – Requires negligible footprint	Compact – Space requirements are minimal and manageable	Moderate – Space-efficient but improvements can be made to reduce the footprint	Large – The system requires a large footprint	Very large – The system requires significant footprint
C6	Health and Safety	Negligible risk - safe to use for all operators	minimal risks - under normal operating conditions	Moderate risk – Risks exist with the system but can be managed by following proper H&S protocols	High risk – requires the operators to follow very extensive safety measures	Very high risk– Significant risks to the operators.

Table 5.3 MCA results

ID	Technology	Operational cost	Ease of asset management	DBPs	Microbiological efficacy - Bacteria	Microbiological efficacy - Protozoa	Microbiological efficacy - Viruses	Footprint	Health and Safety	Total Score	Weighted Score
T1	**Hypochlorite solutions**	4	4	2	5	3	5	3	3	**29**	**3.95**
T2	**Hypochlorite generated by OSE**	3	4	2	5	3	5	2	3	**27**	**3.70**
T3	**Chlorine gas**	3	2	2	5	3	5	3	1	**24**	**3.25**
T4	**Chlorine dioxide**	3	3	2	5	3	5	3	2	**26**	**3.50**
T5	**Chloramines**	3	3	3	3	1	2	3	3	**21**	**2.55**
T6	**Ozone**	2	2	3	5	4	5	3	2	**26**	**3.30**
T7	**Hydrogen peroxide**	3	3	3	3	3	3	3	3	**24**	**3.00**
T8	**Ultraviolet (UV) irradiation**	3	3	4	5	4	4	4	4	**31**	**3.75**
T9	**Reverse Osmosis**	1	2	5	5	5	5	3	4	**30**	**3.45**
T10	**Ceramic Candle Filters (CCFs)**	4	3	5	2	2	1	3	4	**24**	**2.75**

5.2.1 MCA results

Operational cost

Reverse osmosis received the lowest score of 1 due to the requirement for pressurised systems, which are associated with very high operational costs in comparison with the other technologies assessed. Ozone was considered to have high operational costs due to the energy associated with ozone generation. CCFs and hypochlorite solution had the lowest operational costs, both scoring 4. The remaining technologies all scored 3.

Ease of asset management

In this criterion, technologies were assessed based on their complexity of operation and associated training requirements. Hypochlorite solution had the highest score of 4, as this was considered simple to operate with minimal supervision or training. Ozone, RO, and chlorine gas all scored the lowest, each with a score of 2. Ozone requires specific skills training, while RO requires additional treatment processes and regular maintenance to avoid fouling.

DBPs

Technologies with no chemical usage during treatment scored 5; these comprise the two membrane technologies included: RO and CCF. UV was considered as generating low levels of DBPs and so received a score of 4. The chlorination technologies and chlorine dioxide were considered to produce relatively high levels of DBPs, and received a score of 2. Ozone and chloramines received a score of 3, as their propensity to generate DBPs was regarded as intermediate between chlorination technologies and chloramines/ozone. Limited information was available about DBPs from hydrogen peroxide, but a score of 3 was determined as reasonable for this technology. A score of 1 was not awarded to any technology, as it implies a technology that produces significant harmful disinfection by-products (DBPs) with no ability to mitigate or remove them.

Microbial efficacy

CCF received a low score of 1 or 2 depending on the category of microorganism. It demonstrates a poor or fair reduction in microbial load due to its pore size, which may not be small enough to prevent viruses, in particular.

Chloramine is less effective compared to other chemical disinfection technologies, and some microorganisms are highly resistant, resulting in a score of 1-3, depending on the category of microorganism. The various types of chlorination and chlorine dioxide were considered to have good efficacy against protozoa and excellent efficacy against the other two categories of microorganisms.

UV irradiation was scored as having a very good efficacy against viruses and protozoa, and excellent efficacy against bacteria. Ozone was considered to have very good efficacy against protozoa, and excellent against bacteria and viruses.

Reverse osmosis represents a physical barrier capable of excellent removal against all types of microorganisms, and its microbial efficacy scores reflect this, being overall higher than all other technologies. It should be noted that there are issues verifying the performance of RO in this respect, which are not accounted for in this criterion. More information on microbial efficacy is available in Section 4, summarised in Table 4.1 and Table 4.2.

Footprint

Sodium hypochlorite solution produced via onsite electrolysis (OSE) of brine, received the lowest score of 2 (Table 5.3) due to its relatively large space requirements, in comparison with the other technologies, associated with the need for chemical storage and an electrolysis unit. In contrast, all other technologies scored 3, meaning they were considered to have moderate space requirements, with the exception of UV, which earned a score of 4 as this was deemed to be the most compact technology.

Health and Safety

Chlorine gas presents significant risks in terms of safe handling. Its toxicity and high oxidation potential contribute to its low safety score of 1 (Table 5.3), meaning it poses a very high risk to the operator. Chlorine dioxide gas is unstable and can be explosive when pressurised, while ozone leakage may worsen respiratory issues for operators, resulting in a safety score of 2 for both technologies, defined as posing a high risk to operators. All other technologies selected had scores of 3 or 4, with CCF, UV, and RO identified as the safest options regarding operational health and safety, as they were regarded as posing minimal risk to operators under normal operational conditions.

5.2.2 Technologies ranking

The overall ranking of disinfection technologies by MCA is shown in Table 5.4

Table 5.4 Overall ranking of technologies from MCA

Final ranking	Technology	Weighted score
1	Hypochlorite solutions	3.95
2	Ultraviolet (UV) irradiation	3.75
3	Hypochlorite generated by OSE	3.70
4	Chlorine dioxide	3.5
5	Reverse Osmosis	3.45

Final ranking	Technology	Weighted score
6	Ozone	3.3
7	Chlorine gas	3.25
8	Hydrogen peroxide	3
9	Ceramic Candle Filters (CCFs)	2.75
10	Chloramines	2.55

Hypochlorite solution was ranked highest primarily due to microbial efficacy, operational cost, and ease of asset management. However, this technology carries the risk of forming relatively high amounts of DBPs. UV irradiation placed second and performs well across multiple criteria, with relatively high operational costs and asset management challenges.

Chlorine dioxide, reverse osmosis, ozone and chlorine gas were respectively ranked as 4th, 5th, 6th and 7th amongst the selected technologies. They are effective disinfection technologies, but their overall ranking was lower than UV irradiation and hypochlorite because they performed comparatively less well for certain criteria, such as ease of asset management.

Chloramine received average scores in many criteria; however, its lower score in microbial efficacy secured its bottom ranking. It should be noted that in municipal water treatment in the UK chloramines are normally only used to maintain a stable residual in distribution after exposure to free chlorine for a validated contact time (Ct).

CCF was awarded good scores in operational cost and DBPs. These factors are less weighted than microbial efficacy, where CCF received low scores due to its poor or fair microbial efficacy. As with chloramines, CCF is better suited to complement additional disinfection technology. The outcome of this MCA suggests that neither CCF nor chloramines are recommended for use as a primary disinfection method in the treatment of drinking water.

6. Disinfection technologies used overseas

6.1 Introduction

The objective was to critically review the disinfection technologies applied to private and public water supplies internationally, and to assess their suitability to public and private water supplies in England and Wales. The review was conducted as follows:

1. Literature search – Regulatory documents, national guidelines, national/international standards, academic literature (if applicable), and any other relevant material relating to the disinfection of private water supplies was gathered for the following four regions: Global (including developing countries), the European Union, North America (USA/Canada), and Australasia (Australia/New Zealand). In the proposal, only the latter three regions were listed for this section of the report, but during the initial literature search relevant information relating to global technologies, many from the World Health Organization (WHO), were identified, so it was decided to add a subsection for Global disinfection technologies.

2. Initial assessment – alternative disinfection technologies not covered in Sections 3, 4 and 5 of the project were identified, compiled, and shortlisted for further investigation.

3. Suitability evaluation – The applicability of selected alternative technologies to public and private water supplies in England and Wales was assessed, in the context of their advantages/disadvantages as disinfection methods.

The emphasis is on alternative disinfection technologies and those methods regarded as being in widespread use across the globe - chlorine, chloramine, ozone, chlorine dioxide and UV irradiation - will not be discussed in depth in this section.

6.2 Global disinfection technologies

6.2.1 Regulatory background and other information sources

The World Health Organization (WHO) has published several guidelines relevant to the disinfection of public and private water supplies globally.

The WHO Guidelines for Drinking Water Quality: Small Supplies (WHO, 2024) offers recommendations for the application of the broader WHO Guidelines for Drinking Water Quality (2011a) to small water supplies. In this context, the term ‘small supplies’ refers to systems serving a small number of premises, including households, schools, businesses, and hospitals. The Guidelines offer suitability criteria for treatment and disinfection technologies, including water source, priority contaminants, target water quality, efficacy, cost, operational requirements, and adaptability. It is recommended that household water treatment technologies are tested and certified based on their performance or subject to independent product assessments such as the WHO International Scheme to Evaluate Household Water Treatment Technologies (WHO, 2025). This Scheme was established by WHO in 2014, with the objective of assessing the microbial performance of commercially available household water treatment (HWT) technologies against health-based criteria in order to provide guidance on HWT selection for WHO member states. Products are independently evaluated by a panel of experts and testing laboratories. Microbial performance is assessed based on the log removal of bacteria, protozoa, and viruses. The Scheme remains ongoing; the findings of Round I and Round II are publicly available (WHO, 2016; 2019), and newly evaluated products are regularly updated on the WHO website (WHO, 2025). The Scheme has global reach, with assessed products available for sale or distribution in North and South America, Europe, Africa, Asia, and Australasia, comprising nearly 60 countries.

Evaluating household water treatment options: Health-based targets and microbiological performance specifications (WHO, 2011b) is a guidance document that provides recommended methodologies for the evaluation of HWT technologies. The guidance describes commonly used HWT technologies, suitability criteria (particularly regarding application in resource-limited settings), and estimates of microbial removal.

6.2.2 Selected technologies used globally

The WHO Guidelines for Drinking Water Quality (2011a) provides a summary of common household water treatment technologies used globally and their microbial removal efficacy (Table 6.1). It should be noted that these technologies include many which are typically designed for application upstream of a final disinfection step, i.e. partial disinfection through treatment but not necessarily producing water of potable quality. Technologies of potential interest that have not yet been assessed as part of this project include granular media filtration (e.g. granular activated carbon, slow sand filtration), solar disinfection (solar UV + thermal), sedimentation, and multi-barrier approaches (e.g. flocculation-disinfection). Filtration technologies are particularly popular in developing countries due to their ease of operation and minimal energy requirements (WHO, 2011b).

Table 6.1 Selected household water treatment technologies (WHO, 2011)

	Treatment process
Membranes, porous ceramic, or composite filtration	Porous ceramic and carbon block filtration
	Membrane filtration (microfiltration, ultrafiltration, nanofiltration, reverse osmosis)*
	Fibre and fabric filtration (e.g. sari cloth filtration)
Granular media filtration	Rapid granular, diatomaceous earth, biomass and fossil fuel-based (granular and powdered activated carbon, wood and charcoal ash, burnt rice hulls, etc.) filters
	Household-level intermittently operated slow-sand filtration
Solar disinfection	Solar disinfection (solar UV radiation + thermal effects)
Thermal (heat technologies)	Thermal (e.g. boiling)

	Treatment process
Sedimentation	Simple sedimentation
Combination treatment approaches	Flocculation + disinfection systems (e.g. commercial powder sachets or tablets)

The microbial performance of numerous household water treatment products distributed globally has been published as part of the International Scheme to Evaluate Household Water Treatment Technologies ('the Scheme'; WHO, 2025b). The microbial performance of each product is independently rated as follows:

Table 6.2 Microbial efficacy of household water treatment products (WHO, 2025)

Rating	Protection	Log removal
★★★	Comprehensive protection	≥4 log_{10} bacteria ≥5 log_{10} viruses ≥4 log_{10} protozoa
★★	Comprehensive protection	≥2 log_{10} bacteria ≥3 log_{10} viruses ≥2 log_{10} protozoa
★	Targeted protection	Meets performance targets of at least two-star for only two classes of pathogens

A quantitative microbial risk assessment (QMRA) conducted during Round II of the Scheme identified that the health protection afforded by two-star rated products is like that of three-star products under most water quality conditions, assuming that technologies are operated correctly in a consistent manner (WHO, 2019). The current list of products rated two- and three-stars by the Scheme – i.e., providing comprehensive protection – are summarised in Table 6.3. Notable technologies include solar disinfection, multi-barrier approaches (e.g. flocculation-disinfection), and various point-of-use membrane filtration products.

Of all chemical disinfection methods assessed to date through the Scheme, which include chlorination (tablets, electrolytic generation, powder), chlorine dioxide (tablets, solution), hydrogen peroxide (tablets), and colloidal silver (suspension), none have been rated above one-star, owing to the lack of protozoan removal provided by these technologies. The resistance of protozoan pathogens, such as *Cryptosporidium,* to chlorine disinfection is well documented and was reviewed in Section 4 of the report. Consistently high removal of bacteria and viruses, but poor-to-moderate removal of protozoa in the global technologies reviewed were consistent with this evidence. While chlorine is recommended by WHO for potable water disinfection, its guidance highlights that a multi-barrier approach may be required to enhance protection against protozoa in source water (WHO, 2011).

Table 6.3 Products meeting WHO microbial performance criteria (Comprehensive protection only) (WHO, 2025)

Performance classification	Product	Manufacturer	Technology type
Comprehensive protection (***)	AquaPak	Solar Solutions LLC	Solar disinfection
Comprehensive protection (***)	Grifaid Family Filter	The Safe Water Trust Ltd	Membrane filtration
Comprehensive protection (***)	LifeStraw Community	LifeStraw SA (part of the Vestergaard Group)	Membrane filtration
Comprehensive protection (***)	LifeStraw Family 1.0	LifeStraw SA (part of the Vestergaard Group)	Membrane filtration
Comprehensive protection (***)	ORISA®	Fonto De Vivo	Membrane filtration
Comprehensive protection (***)	SolarBag®	SolarBag, Inc	Solar disinfection
Comprehensive protection (**)	AquaSure Tab10	AquaSure	Flocculation-disinfection
Comprehensive protection (**)	DayOne Waterbag™	DayOne Response Inc	Flocculation-disinfection-filtration
Comprehensive protection (**)	Drop2Drink Unit	D2D Water Solutions BV	UV disinfection and membrane filtration
Comprehensive protection (**)	JAMEBI Solar Water Pasteurizer	Relevant Projects Ltd	Solar disinfection
Comprehensive protection (**)	LifeStraw Family 2.0	LifeStraw SA (part of the Vestergaard Group)	Membrane filtration
Comprehensive protection (**)	P&G™ Purifier of Water	The Procter and Gamble Company	Flocculation-disinfection
Comprehensive protection (**)	PuriBag	Praqua Pty Ltd	Flocculation-disinfection-filtration
Comprehensive protection (**)	ROAMfilter™ Plus	Wateroam Pte Ltd	Membrane filtration
Comprehensive protection (**)	Sydney 905 Purifier	Sydney 905 Filters (Pty) Ltd	Membrane filtration
Comprehensive protection (**)	Waterlogic Hybrid/Edge Purifier	Qingdao Waterlogic Manufacturing Company	UV disinfection

6.3 Disinfection technologies used in the EU

6.3.1 Regulatory background and other information sources

The regulation of disinfection technologies in the European Union (EU) is governed by the Biocidal Products Regulation (BPR, Regulation (EU) 528/2012). This regulation ensures that biocidal products used for disinfection are safe for human health and the environment. Additionally, the Drinking Water Directive (Directive (EU) 2020/2184) sets standards for the quality of water intended for human consumption, including disinfection requirements.

Member states must also adhere to national regulations that align with EU directives while considering regional conditions. Member States may, for a limited time, deviate from certain chemical quality standards. This process is called “derogation.” Derogation can be granted, provided it does not constitute a potential danger to human health, and provided that the supply of water intended for human consumption in the area concerned cannot be maintained by any other reasonable means. Disinfection requirements vary between member states, for example, with respect to water source.

In addition to EU regulations, several other sources provide information on disinfection technologies. These include:

- The European Chemicals Agency (ECHA), which maintains databases on approved biocidal products and their active substances (ECHA, 2023).
- The European Centre for Disease Prevention and Control (ECDC), which offers guidelines on public health-related disinfection (ECDC, 2020).
- National regulatory bodies and water utilities

6.3.2 Selected technologies used in the EU

Disinfection methods identified in the above sources align with widespread technologies reviewed in Section 4, i.e., chlorine, chloramine, ozone, chlorine dioxide and UV irradiation.

6.4 Disinfection technologies used in the USA and Canada

6.4.1 Regulatory background

In the United States, the Environmental Protection Agency (EPA) regulates disinfection technologies under the Safe Drinking Water Act (SDWA). The EPA sets maximum contaminant levels (MCLs) and disinfection requirements to ensure safe drinking water. The National Sanitation Foundation (NSF) also provides certification for water treatment products.

In Canada, the regulation of drinking water is primarily under provincial and territorial jurisdiction, but ‘Health Canada’ provides national guidelines through the Guidelines for

Canadian Drinking Water Quality. These guidelines establish recommended limits and best practices for water treatment, including disinfection. Additional sources of information on disinfection technologies in the US and Canada include:

- The Centers for Disease Control and Prevention (CDC), which provides guidance on waterborne pathogens and public health protection (CDC, 2024).
- The American Water Works Association (AWWA), which publishes research and standards on water treatment (AWWA, 2025).
- The Water Research Foundation (WRF), which conducts studies on emerging water treatment technologies (WRF, 2023).

6.4.2 Selected technologies used in the USA and Canada

Disinfection technologies used in specific areas of the US and Canada but not commonly employed in England and Wales include:

- Mixed Oxidant Solution (MOS) disinfection is an emerging technology being utilised in certain water treatment facilities across the US (MIOX, 2018).
- Peracetic acid disinfection is approved by USEPA for use in wastewater and combined sewage disinfection (USEPA, 2012) and by the US Food and Drug Administration (FDA) for various other applications including food, aquaculture, and healthcare industries (Luukkonen *et al.*, 2016)

6.5 Disinfection technologies used in Australia and New Zealand

6.5.1 Regulatory background and other information sources

Australia

The Australian drinking water guidelines state that, “With the exception of bottled or packaged water, the Guidelines apply to any water intended for drinking irrespective of the source” (National Health and Medical Research Council, 2024). Therefore, private suppliers are subject to the same rules as municipal suppliers. The guidance refers to small water supplies as those serving less than 1000 people and describes that due to limited data and monitoring resources, these are initially given a conservative microbial risk classification (National Health and Medical Research Council, 2024). Additionally, depending on the size of distribution system and water age, small water supplies do not necessarily require a residual disinfectant concentration. While these guidelines set out best practice they are not legally enforced, and their implementation is at the discretion of each state and territory (National Health and Medical Research Council, 2024).

New Zealand

The Water Services (Drinking Water Standards for New Zealand) Regulations 2022 provide the basis for other legislation related to drinking water quality. These regulations detail public health standards and compliance criteria but do not contain specific information about how water quality should be managed. That information is contained within the 'Guidelines for Drinking-water Quality Management in New Zealand' (Ministry of Health, 2019).

The 2022 Drinking Water Quality Assurance Rules 'The Rules', prepared by the New Zealand government, designate supplies based on population served. The Rules require microbial monitoring for all designations (Taumata Arowai, 2022). These rules state that one or more of the following options must be used to demonstrate bacterial compliance: chlorine, chlorine dioxide, ozone, UV light. Based on the size and type of private supply, different rules are enforced, with certain supply categories requiring chlorination to meet bacterial compliance (Taumata Arowai, 2022). The Rules were revised in 2024, effective January 2025, aimed at simplifying requirements and application, including end-point treatment (disinfection) and monitoring requirements with a focus on public health. Taumata Arowai are actively consulting with stakeholders around 'Acceptable Solutions' for drinking water treatment, the latest consultation closed on 13th June 2025.

6.5.2 Selected technologies used in Australia and New Zealand

Australia

The drinking water guidelines list a number of common disinfection methods, the same as those reviewed in Section 4, i.e., chlorine, chloramine, ozone, chlorine dioxide and UV irradiation. The Australian guidelines take a similar risk-based approach to UK regulations, describing best practice for selecting an appropriate disinfection strategy. This approach determines the disinfection requirements based on what hazards are identified within a specific supply.

Through review of federal and state-level guidance on drinking water disinfection it can be concluded that the disinfection methods employed in Australia correspond with those used in England and Wales. In other words, it is unlikely that any technologies which would be termed alternative disinfection methods within the context of this project are currently in use.

New Zealand

There are some alternative disinfection technologies listed in the 'Guidelines for Drinking-water Quality Management in New Zealand'. These strategies can be used in New Zealand after log removal assessment by the Ministry of Health has proved efficacy against one or all of the following: bacteria, viruses, protozoa. Among these methods are a number of alternative disinfection technologies not known to be used for private or public water treatment in England and Wales: bromine, iodine, silver and other metal ions and solar disinfection (Ministry of Health, 2019).

6.6 Evaluation of suitability for English and Welsh water supplies

Due to the varying quantity and quality of available information – particularly regarding microbial efficacy and large-scale application in potable water systems – a formal multi-criteria analysis was deemed inappropriate. A consistent rating of all technologies could not be reliably achieved using this approach. Instead, a qualitative assessment was conducted, based on a critical review of advantages and limitations drawn from grey literature and peer-reviewed sources, with a focus on performance for the removal and/or inactivation of microorganisms.

An overview of the technologies selected for assessment and their associated benefits and limitations are summarised in Table 6.4. A more detailed summary of the microbial efficacy of each technology is provided in Table 6.5. The suitability of each disinfection technology is discussed below.

6.6.1 Physical removal

Several filtration technologies were reviewed, all of which share general limitations identified in Section 4 of the report, including:

- Variation in microbial removal due to differing/undefined pore size, flow rate, and media properties, with particular challenges associated with viral removal
- Requirement for routine replacement of filter media/membrane to prevent clogging and inconsistent performance
- Need for periodic chemical cleaning to address biofouling

Of the physical removal methods summarised in Table 6.4 (carbon block filtration, rapid granular/diatomaceous earth/biomass/fossil fuel-based filtration, fibre and fabric filtration, hollow fibre ultrafiltration, slow sand filtration, and sedimentation), several are considered unsuitable for application as disinfectants in England and Wales due to limited microbial removal. Fibre and fabric filtration, for example, achieves limited bacterial and protozoan removal and is ineffective against viruses. This technology is typically used in low-resource settings (WHO, 2011). Other filtration methods – such as slow sand, rapid granular, and carbon block filtration – also exhibit limited viral removal and require optimal operational conditions to achieve adequate removal of bacteria and protozoa (WHO, 2011). Sedimentation provides poor removal across all three microbial classes. Consequently, these physical removal methods are generally recommended only when followed by a final disinfection step, such as chlorination, to ensure microbial safety (WHO, 2011).

Of all reviewed filtration technologies, hollow fibre ultrafiltration showed the strongest microbial removal performance under optimised conditions (WHO, 2011). Several devices based on this technology have received WHO's 'Comprehensive Protection' classification (WHO, 2025).

These systems are designed for Point-of-Use (POU) applications and would require scale-up for use in larger private or public potable water supplies in England and Wales.

Recommendations: Ultrafiltration technologies warrant further investigation regarding their performance in private or public potable water supplies in England and Wales.

6.6.2 Thermal disinfection

Thermal disinfection involves the application of heat to inactivate microbial contaminants in water (Table 6.4). The most common form is boiling, which can inactivate microorganisms through thermal denaturation of cellular proteins and membranes (Cebrián, 2017). This approach is used at a household-scale widely in emergency and field-based settings, with lower energy methods (e.g. pasteurization) applied for household water disinfection in low-resource areas (WHO, 2011; Cebrián, 2017). Boiling is considered highly effective for the removal of a wide spectrum of bacteria, viruses, and protozoa (Table 6.5; WHO, 2011). As such, it is routinely recommended by public health authorities and water companies in the UK during 'boil water notices' issued in response to microbial contamination events in drinking water supplies.

The high energy demands of thermal disinfection make it impractical for routine application in potable water supplies. It is also unsuitable for large-scale treatment due to scalability and cost limitations (Letcher, 2022). These limitations preclude the application of thermal disinfection to potable water supplies in England and Wales.

Recommendations: Unsuitable for application in England and Wales outside of established short-term approaches, e.g., during boil water notices.

6.6.3 Chemical disinfection

Mixed oxidant solution

Mixed oxidant solution (MOS) is a disinfectant composed primarily of chlorine, in addition to other oxidant species such as hydrogen peroxide, chlorine dioxide, and ozone (Table 6.4). US-based MIOX Corporation has emerged as the leading manufacturer of this technology in western countries, with MIOX products applied to municipal supplies in 'more than 2000' sites in North and South America (MIOX, 2018).

MOS is generated via the electrolysis of sodium chloride (brine). This process is in principle similar to onsite chlorine generation (OSE, Section 4 of this report), however manufacturers claim that the precise conditions of the electrolysis process are optimised to promote the formation of additional oxidants (Bradford, 2011). The exact composition of MOS has proven challenging to define due to a lack of analytical techniques capable of differentiating oxidant species at low concentrations. At present, only the presence of hydrogen peroxide has been confirmed using chemiluminescence techniques, with the presence of ozone and chlorine dioxide uncertain and inferred using other indirect means (MIOX, 2011). The stability of these additional oxidant species is unclear and their contribution to disinfection remains uncertain (Bradford, 2011).

Despite these uncertainties, MOS is a broad-spectrum disinfectant with reported microbial removal comparable to chlorine (Table 6.5; Geldenhuys, 2000). Several studies report improved performance against bacterial and viral indicators in comparison to chlorine, including resistant cell types such as spores (Bradford, 2011); however, others indicate no significant difference between the two disinfectants (Choi *et al.*, 2022; Geldenhuys, 2000; WHO, 2004; WRc, 1997). Early studies indicated superior inactivation of *Cryptosporidium* by MOS compared to chlorine, though these findings have not been replicated in recent years (Bradford, 2011). MOS is also reported to produce up to 50% less disinfection byproducts (DBPs) than chlorine (MIOX, 2018), with one case study indicating that use of MOS as a pretreatment step led to a reduction of DBPs in distribution (Bradford, 2011). However, an increased risk of brominated DBP formation in high bromide waters was also identified in the same report (Bradford, 2011).

An independent experimental study of MOS products from two manufacturers (MIOX and STEL) conducted by WRc (1997) reported the following conclusions:

- Oxidant species other than hypochlorous acid and hypochlorite ion could not be identified in MIOX and STEL MOS, though behaviours of MIOX MOS in response to various experimental techniques indicated the presence of unidentified oxidant/s.

- No direct evidence was found for the presence of oxidants stronger than hypochlorous acid and hypochlorite ion in MIOX or STEL MOS.

- No significant difference in disinfection efficacy between MIOX and STEL MOS and commercial hypochlorite in the disinfection of *Clostridium* spores or poliovirus was reported.

Understanding of MOS generally suffers from a lack of independent assessment of its efficacy, as many resources associated with this technology, particularly in more recent years, stem from its manufacturers as opposed to independent bodies. While this technology shows promise regarding microbial removal and DBP reduction, there is a lack of consistent and independent data regarding its efficacy as a disinfectant to date. Further research is required to understand the actual disinfection capability of MOS in UK water supplies and whether it presents a viable alternative to chlorination in England and Wales.

Recommendations: Warrants further investigation regarding its performance in potable water disinfection.

Peracetic acid

Peracetic acid (CH_3CO_3H, PAA) is an organic peroxide disinfectant that is sold as a ready-to-use equilibrium solution comprising acetic acid, hydrogen peroxide, and water (Table 6.4). Its degradation in water generates free radical species of high oxidating potential, such as hydrogen peroxyl and hydroxyl, which damage microbial cell membranes, resulting in cell lysis (USEPA, 2012). PAA has been applied as a disinfectant chiefly in wastewater disinfection, with additional applications for surface and water disinfection in healthcare, food, and aquaculture (Paggiaro *et al.*, 2024; USEPA, 2012). Use of PAA in potable water disinfection is limited to a small number of academic studies at present.

PAA is reported to be a fast acting and effective disinfectant, with microbial removal generally reported to be similar to chlorine (Luukkonen *et al.*, 2016). Some evidence suggests improved protozoan destruction in agricultural contexts (McCaughan *et al.*, 2024). A key benefit reported for PAA is that is it environmentally benign; it was not found to produce measurable DBPs and its breakdown products (carbon dioxide and water) can be released safely into the environment (Paggiaro *et al.*, 2024; USEPA, 2012). However, the instability of PAA makes maintaining a consistent residual in water challenging and necessitates careful handling and storage of the solution (Luukkonen *et al.*, 2016). PAA is also reported to contribute to increased organic content in water, though the impacts of this on biofilm formation in potable supplies have not been quantified (Paggiaro *et al.*, 2024).

Studies of the use of PAA in surface water and groundwater disinfection exist but are limited in number (Luukkonen *et al.*, 2016), and it has not been applied on a large scale to any potable water supplies globally to our knowledge. Considering the potential benefits of this disinfectant, further research into its use in potable water disinfection in England and Wales is likely to be of value.

Recommendations: Warrants further investigation regarding its performance in potable water disinfection

Bromine

Bromine is a halogen oxidising agent with a lower oxidating power than chlorine (Table 6.4). It is most commonly used as an alternative disinfectant to chlorine for swimming pools, water fountains, and cooling towers. It has been less frequently applied to potable water disinfection in non-residential settings such as ships and oil/gas rigs (WHO, 2018).

Bromine has been reported to achieve similar or superior microbial removal to chlorine, though there is considerably less data available regarding the efficacy of bromine, particularly in potable water supplies (Table 6.5). Several studies indicate that bromine may afford greater removal than chlorine of protozoan species *C. parvum* and *Entamoeba histolytica*; however, its biocidal effect on other key protozoan pathogens such as *Giardia* remains unstudied (WHO, 2018). An important benefit of bromine as a disinfectant lies in its efficacy in the presence of ammonia. Bromamines, which form through a reaction between bromine and ammonia/amines, are widely reported to be more effective disinfectants than chloramines for bacteria, viruses, and protozoa (WHO, 2018). Additionally, bromine can operate effectively at a wider pH range than chlorine (pH 6-8.5), (WHO, 2018).

The application of bromine as an alternative disinfectant in potable water supplies is limited by the heightened health risks associated with brominated DBPs in comparison to their chlorinated analogues. The safety of long-term consumption of water treated with bromine have not been determined, and as such WHO do not recommend the use of bromine as a primary disinfectant due to DBP-associated toxicity concerns (WHO, 2018). At present, the efficacy of bromine in comparison to chlorine is promising but is understudied in potable supplies. A better understanding of the health risks associated with bromine disinfection are required before this disinfectant should be applied to potable water supplies in England and Wales.

Recommendation: Warrants further investigation, especially regarding health risks associated with brominated DBPs and its performance in disinfection of potable water

Iodine

Iodine is a halogen oxidising agent with a lower oxidating power than chlorine and bromine (Table 6.4). Iodine-based tablets have been applied to field-based potable water disinfection (e.g. emergency responses, military operations, recreational activities). Iodine is reported to be a less effective disinfectant than chlorine and bromine, notably protozoa and viruses (Table 6.5; WHO, 2018). Long term exposure to iodine is associated with thyroid dysfunction (hypothyroidism), especially in vulnerable groups such as pregnant women and neonates (WHO, 2018). Iodinated DBPs also present associated health risks. Due to the toxicity and health impacts associated with iodine, WHO do not recommend its use for the disinfection of potable supplies (WHO, 2018). The sub-optimal disinfection efficacy and health risks associated with iodine preclude its application to potable supplies in England and Wales.

Recommendations: Unsuitable for application in England and Wales

Silver ions

Silver ions have been used as alternative disinfectants in some applications due to their biocidal properties (Table 6.4). Ionic silver is generally derived from a solution of silver salts such as silver nitrate and silver chloride. There is a lack of consistent data regarding the microbial efficacy of silver ions, though studies suggest that it provides only poor protection against viruses and protozoa (Table 6.5; WHO, 2018). As a result, silver does not meet the WHO minimum performance recommendations for point of use treatment products (effective removal of two of the three pathogen classes) and is thus not recommended by WHO for the disinfection of potable water supplies (WHO, 2018). Considering these findings, it can be concluded that silver ions are not suitable for the disinfection of potable water supplies in England and Wales.

Silver ions have been used to increase the efficacy of filtration devices (Section 4.9.2 of this report); however, the relative contribution of silver to microbial removal in this context is difficult to discern from that of the filter itself, and as such, this application was not considered in the evaluation of silver as a disinfectant.

Recommendations: Unsuitable for application in England and Wales

6.6.4 Solar disinfection

Solar disinfection involves the exposure of water in transparent containers to natural sunlight, facilitating microbial inactivation via ultraviolet (UV) and thermal effects (Table 6.4; WHO, 2011). This method has been widely applied for potable water disinfection in low-resource or emergency settings, particularly in areas of the developing world that receive abundant sunlight (Letcher, 2022).

Solar disinfection is reported to achieve a high level of microbial removal under optimal conditions (Table 6.5; WHO, 2011). However, the performance of this technology relies heavily on environmental conditions that are difficult or impossible to control. The efficacy of solar disinfection is highly dependent on ambient sunlight levels and water temperature, both of which are subject to considerable seasonal and geographic variation in the UK. During overcast conditions or winter months in temperate climates, the UV intensity may be insufficient to achieve the required microbial removal within acceptable timeframes (up to 48 h in cloudy conditions; Letcher *et al.*, 2022). Additionally, the batch-based nature of solar disinfection makes it impractical for implementation in a larger private/commercial supply, which requires continuous flow of consistent quality.

Given these limitations, particularly the dependence on weather conditions, solar-based infection is not considered to be appropriate for the disinfection of potable water supplies in England and Wales.

Recommendations: Unsuitable for application in England and Wales

6.6.5 Combination treatment approaches

Combination treatment methods apply a multi-barrier approach by integrating physical and chemical treatment processes (Table 6.4). The most frequently documented method during the review of global technologies was coagulation/disinfection, which is typically delivered in the form of sachets or tablets containing a coagulating/flocculating agent (such as ferric sulphate) and a disinfectant e.g. calcium hypochlorite (WHO, 2025). Upon addition to a defined volume of water, the coagulant facilitates the aggregation and settling of suspended solids and microbes, and the disinfectant inactivates remaining contaminants. The treated water is usually then subject to a simple filtration step to remove the flocculated solids prior to consumption (WHO, 2011).

Coagulation and disinfection as a single step is reported to provide good removal of bacteria, viruses, and protozoa. Several products have been deemed to provide ‘Comprehensive

Protection' by WHO (Table 6.5; WHO, 2025). This technology is particularly useful in the treatment of highly turbid waters, which may otherwise reduce the efficacy of a disinfectant used alone (Pooi and Ng, 2018). However, these products are intended for point-of-use applications, requiring adequate mixing and settling times to ensure effective treatment (WHO, 2011). Their practicality for larger or plumbed systems that require ongoing treatment and flow may therefore be limited.

In England and Wales, coagulation/disinfection point-of-use approaches are likely better suited to small-scale or remote supplies treating turbid surface waters, particularly where conventional infrastructure is lacking or intermittent.

Recommendations: Unsuitable for application in England and Wales except in low resource/remote supplies treating turbid surface waters

Table 6.4 Selected alternative disinfection technologies used in overseas countries

	Disinfection Method	Regions of use	Mechanism of action	Benefits	Limitations
Physical removal	Carbon block filtration	Global[1]	Filtration via adsorption using activated carbon[1]	Can achieve good removal of bacteria and protozoa in optimal conditions[1]. Greater efficiency than GAC filtration due to larger surface area[2]	Efficacy varies depending on pore size and flow rate[1] Generally ineffective for viruses[1]. Prone to clogging with long-term use[2]. Biofouling may necessitate chemical cleaning and backwash, particularly for high DOM water sources[4]
	Rapid granular, diatomaceous earth, biomass & fossil fuel-based filter media	Global[1]	Filtration via adsorption using granular and powdered activated carbon, wood and charcoal ash, burnt rice hulls, etc.[1]	Can achieve moderate removal of bacteria, protozoa and viruses in optimal conditions[1]. Inexpensive[3]	Efficacy varies considerably depending on media size and properties, flow rate and operation conditions[1]. Filter media requires routine replacement to ensure consistent filtration[2]
	Fibre and fabric filtration	Global[1]	Membrane filtration[1]	Inexpensive[3]	Poor microbial removal and ineffective for viruses[1]. Limited scalability[2]. Biofouling may necessitate chemical cleaning and backwash, particularly for high DOM water sources[4]
	Hollow fibre ultrafiltration	Global[1]	Membrane ultrafiltration[1]	Can achieve good removal of bacteria, protozoa, and viruses in optimal conditions[1]	Efficacy varies with pore size, integrity of filter medium and filter seals, and resistance to chemical and biological degradation[1] Biofouling may necessitate chemical cleaning and backwash, particularly for high DOM water sources[4]
	Slow sand filtration (biosand)	Global[1]	Filtration through sand and gravel bed; biological “schmutzdecke” layer contributes to microbial removal[2]	Some removal of bacteria and protozoa[1] Minimal energy requirements[3] Resources required are low-cost and widely available[3]	Efficacy varies with filter maturity, operating conditions, flow rate, grain size, and filter bed contact time[1]. Poor viral removal[1]. Combination with downstream disinfection recommended[2]. Generally slow flow rate[3]

	Disinfection Method	Regions of use	Mechanism of action	Benefits	Limitations
	Sedimentation	Global[1]	Settling of particle-associated and large microbes via gravity[1]	Some removal of large and particle-associated microbes[1]	Generally poor microbial removal[1]
Solar disinfection	Solar disinfection	Global[1], EU, New Zealand[4]	Microbial inactivation via solar UV and thermal effects[2]	Effective against certain bacteria, viruses and protozoa but dependant on solar intensity[1,4]. Inexpensive, minimal energy requirements[2]	Inconsistent levels of sunlight and potentially unsatisfactory inactivation of microorganisms[1,4]. Variation depending on oxygenation, exposure time, temperature, turbidity, water depth[1]. Long contact times required (>6-48 h)[2]
Thermal disinfection	Thermal (heat technologies)	Global[1]	High temperatures inactivate microorganisms via the thermal denaturation of proteins, nucleic acids, and lipid bilayers. Can be achieved by boiling or pasteurisation[6]	Excellent removal of bacteria, protozoa, and viruses[1]	High energy requirements make technology incompatible with scale-up[2]. Release of particulate emissions depending on heat source used[2]. Taste issues[2]. Some cell types (e.g. spores) are more resistant, requiring treatment at a specific temperature and time to ensure removal[1]
Chemical disinfection	Mixed Oxidant Solution (MOS)	USA, New Zealand[4]	Oxidant[9] Generated via onsite electrolysis of brine to produce hypochlorous acid and a mixture of other oxidants including sodium hypochlorite, ozone, hydrogen peroxide, and chlorine dioxide[9]	Good microbial efficacy, reportedly better than chlorine in some studies[9] Generates fewer DBPs than chlorine[9]	Requires specialised equipment for mixing and monitoring[9] Persistence/long-term stability of oxidant compounds unclear[9]. Efficacy against protozoa is unclear[9]. Produces more brominated DBPs than chlorine in high bromide waters[9]. Lack of consistent scientific evidence regarding oxidant composition, disinfection efficacy, and benefits over chlorination/on-site generation[4,10]
	Bromine	EU, USA[5], New Zealand[4]	Oxidant[4]	Similar efficacy to chlorine and potentially more effective against protozoa[4]. More effective disinfectant than chlorine for ammonia containing waters (bromoamines are stronger oxidants than chloramines)[4,5]	High cost and difficulty in handling due to high propensity to corrode[4]. Brominated DBPs considered more toxic than chlorinated DBPs; limits application to municipal water treatment[5]. Some cell types e.g. spores demonstrate resistance[5]

	Disinfection Method	Regions of use	Mechanism of action	Benefits	Limitations
	Iodine	New Zealand[4]	Oxidant[4]	Similar efficacy to chlorine but with slower action[4]. Lower disinfectant demand than chlorine[4]. May provide superior disinfection to chlorine for poor quality waters[4]	High cost and potential for taste and odour issues. Additionally, there are potential health impacts from long term exposure in drinking water[4]. Toxic DBP formation[4.] Limited protozoa removal[4]
	Peracetic acid	EU, USA[7]	Oxidant[7]	Does not generate DBPs[7]. Non-toxic breakdown products – environmentally friendly[8]. More rapid than chlorine-based disinfectants[7]. Similar microbial efficacy to hypochlorite and UV, with potentially superior inactivation of protozoa under optimised conditions[8,11,12]. Long shelf life (6 months-2 years)	Limited information regarding efficacy in drinking water; currently only established as an alternative disinfectant for wastewater treatment, food production, aquaculture, and healthcare industries[8]. Challenging to maintain residual due to rapid decomposition in water, particularly in alkaline conditions[8,11]. Potentially greater risk of biofilm formation due to residual carboxylic acids[8]. Expensive[8]. Requires careful handling due to corrosivity and instability[8]
	Silver ions	EU, New Zealand[4]	Damages proteins and cell membranes (oligodynamic effect)[3]	Long-lasting residuals[4] Copper/silver ionisation has been successfully used to control *Legionella* in hospital hot water systems[13]	Not recommended by WHO for use as a primary disinfectant[13.] Generally poor disinfection with long contact times and high concentrations required[4.] Does not meet the WHO Minimum performance requirements which require effectiveness in at least two of the three pathogen classes[4,13]. Few studies conducted in field conditions[13]
Combination approaches	Combination treatment approaches (Flocculation + disinfection)	Global[1]	A coagulant/flocculant e.g. ferric sulphate aggregates suspended particles and microorganisms. Combined with chemical disinfection, usually chlorination[3]	Minimal energy requirements[2] Physical removal is a beneficial addition in turbid waters[3]	Inconsistent performance depending on dose[3] Flocculant efficiency may be impacted by temperature and pH[3]

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Table 6.5 Selected alternative disinfection technologies used in overseas countries – Microbial removal efficacy

	Disinfection Method	Bacteria	Protozoa	Viruses
Physical removal	Carbon block filtration	Can achieve good removal but efficacy varies with pore size and flow rate (2-6 LRV*)[1]	Can achieve good removal but efficacy varies with pore size and flow rate (4-6 LRV)[1]	Generally poor removal; efficacy varies with pore size and flow rate (1-4 LRV)[1]
	Rapid granular, diatomaceous earth, biomass and fossil fuel–based	Can achieve moderate removal but efficacy varies with media size and properties, flow rate and operation conditions (LRV >1-4)[1]. MINCH Household Water Filter (diatomaceous earth) reported to achieve ≥2 LRV[2]	Can achieve moderate removal but efficacy varies with media size and properties, flow rate and operation conditions (LRV >1-4)[1]. MINCH Household Water Filter (diatomaceous earth) reported to achieve ≥2 LRV[2]	Can achieve moderate removal but efficacy varies with media size and properties, flow rate and operation conditions (LRV >1-4)[1]
	Fibre and fabric filtration	Poor removal (1-2 LRV)[1]. Ineffective for dispersed bacteria[1]	Poor removal (0-1 LRV)1. Larger protozoa (>20 µm) may be removed, but ineffective for small protozoa e.g. *Giardia*, *Cryptosporidium*[1]	No removal[1]
	Hollow fibre ultrafiltration	Can achieve good removal in optimised conditions (3-6 LRV)[1]. Products inc. LifeStraw and ORISA® reported to achieve ≥4 LRV[2]	Can achieve good removal in optimised conditions (3-6 LRV)1. Products inc. LifeStraw and ORISA® reported to achieve ≥4 LRV[2]	Can achieve good removal in optimised conditions (3-6 LRV)1. Products inc. LifeStraw and ORISA® reported to achieve ≥5 LRV[2]
	Slow sand filtration	Can achieve moderate removal but varies with filter maturity, operating conditions, flow rate, grain size, and filter bed contact time (1-3 LRV)[1]	Can achieve moderate removal but varies with filter maturity, operating conditions, flow rate, grain size, and filter bed contact time (2-4 LRV)[1]	Poor removal (0.5-2 LRV)[1]
	Sedimentation	Poor removal (0-0.5 LRV). Only removes particle-associated and large settleable microbes[1]	Poor removal (0-1 LRV). Only removes particle-associated and large settleable microbes[1]	Poor removal (0-0.5 LRV). Only removes particle-associated and large settleable microbes[1]

	Disinfection Method	Bacteria	Protozoa	Viruses
Solar disinfection	Solar disinfection	Good removal is possible, but optimised conditions are required (LRV >3-5)[1]. SolarBag® and AquaPak are reported to achieve ≥4 LRV[2]	Good removal is possible, but optimised conditions are required (LRV >2-4)[1]. SolarBag® and AquaPak are reported to achieve ≥4 LRV[2]	Good removal is possible, but optimised conditions are required (LRV >2-4)[1]. SolarBag® and AquaPak are reported to achieve ≥5 LRV[2]
Thermal disinfection	Thermal (heat technologies)	Excellent removal (>6-9 LRV), though spores are more resistant to removal than vegetative cells[1]	Excellent removal (>6-9 LRV), though certain cell types are more resistant than others	Excellent removal (>6-9 LRV)[1]
Chemical disinfection	Mixed Oxidant Solution (MOS)	Reportedly greater efficiency than chlorine against bacteria (including spores)[5]	Inconsistent performance against *Cryptosporidium* oocysts in experimental studies[4,5]	Reportedly greater efficiency than chlorine against viruses (MS2 coliphage)[5]
	Bromine	Similar efficacy to chlorine[3]. Similar to chlorine, some cell types demonstrate resistance e.g. spores[3]. Bromamines (i.e. use of bromine in presence of ammonia) more effective than chloramines for bacterial removal[3]	Similar efficacy to chlorine; may be more effective for protozoan removal (reported for *Entamoeba histolytica* and *Cryptosporidium parvum)*[3]. No data for *Giardia* inactivation[3]. Bromamines (i.e. use of bromine in presence of ammonia) more effective than chloramines for protozoan removal[3]	Similar efficacy to chlorine[3]. Bromamines (i.e. use of bromine in presence of ammonia) more effective than chloramines for viral removal[3]
	Iodine	Good bacterial removal[4]	Ineffective against *Cryptosporidium*; long contact times required to inactivate *Giardia*[4]	High Cts required for adequate viral removal, particularly at low pH and temperature[4]
	Silver ions	Adequate bacterial removal can be achieved but long contact times are required, and LRV vary widely between studies[9]. Silverdyne®, a colloidal silver suspension, achieved 2 LRV of bacteria[2]	Limited data regarding protozoan removal[9]	Limited data regarding viral removal[9]. Silverdyne®, a colloidal silver suspension, did not meet the WHO minimum viral removal target, achieving only 0.2 LRV of MS2 coliphage[2]
	Peracetic acid	Similar disinfection efficacies to hypochlorite reported, with some cell types (spores) demonstrating resistance[6,7]	Similar or superior disinfection efficacies to hypochlorite reported for protozoa including *C. parvum* and *Entamoeba tenella*[6,8]	Good viral removal, though some reports indicate that peracetic acid is less efficient for the removal of viruses (coliphage) than hypochlorite[6,7]

	Disinfection Method	Bacteria	Protozoa	Viruses
Combination approaches	Combination treatment approaches (Flocculation + disinfection)	Excellent removal (7-9 LRV). AquaSure Tab10 reported to achieve ≥7.5 LRV for *E. coli*[2]	Good removal (LRV 3-5). Some removal of *Cryptosporidium* is possible with coagulation step1. AquaSure Tab10 reported to achieve ≥2 LRV for *C. parvum*[2]	Good removal (LRV 4.5-6)[1]
References		1. World Health Organization (WHO), (2011) Guidelines for drinking-water quality. 4th edn. Geneva: WHO. 2. World Health Organization (WHO), (2025) International scheme to evaluate household water treatment technologies. Available at: https://www.who.int/tools/international-scheme-to-evaluate-household-water-treatment-technologies/products-evaluated (Accessed: March 2025). 3. World Health Organization (WHO), 2018. Bromine in drinking-water: use for water disinfection and potential health effects. 4. Ministry of Health (2019) 'Guidelines for Drinking-water Quality Management in New Zealand'. 5. Bradford, W. (2011). The Differences between On-Site Generated Mixed-Oxidant Solution and Sodium Hypochlorite (aka the Master Features Summary). MIOX Corporation. 6. Luukkonen, T. and Pehkonen, S.O. (2016). Peracids in water treatment: A critical review. Critical Reviews in Environmental Science and Technology, 47(1), pp.1–39. 7. Kauppinen, A., Ikonen, J., Pursiainen, A., Pitkänen, T. and Miettinen, I.T. (2012). Decontamination of a drinking water pipeline system contaminated with adenovirus and Escherichia coli utilizing peracetic acid and chlorine. Journal of Water and Health, 10(3), pp.406–418. 8. McCaughan, K.J., Scott, Z., Rock, C. and Kniel, K.E. (2024). Evaluation of aqueous chlorine and peracetic acid sanitizers to inactivate protozoa and bacteria of concern in agricultural water. Applied and Environmental Microbiology. 9. World Health Organization (WHO), 2018. Alternative drinking-water disinfectants: bromine, iodine and silver		

7. Conclusions and recommendations

7.1 Conclusions

7.1.1 Context of the term 'commercial applications'

In the context of the public and private water supplies in England and Wales, a commercial activity/premise/application is where potable water derived from a private supply system is consumed by a commercial activity. Examples include during food or drink production intended for human consumption, or a hotel using a private water supply for domestic purposes. In contrast, public applications or activities are where potable water from a private supply is available for public consumption. This includes public buildings, such as education providers, hostelries and exhibitions.

DWI and WRc concluded that the distinction between public and commercial applications is often unimportant from an applied regulatory or public health perspective. Therefore, it was decided that both applications were within the project scope. Public water supplies were defined in this context as situations where there is disinfection of a public water supply before onsite distribution e.g. a hospital or apartment block with onsite disinfection and distribution with privately owned plumbing.

7.1.2 Local authority surveys and water company enquiries

A total of 118 English and Welsh local authorities responded to two surveys sent out during the project. All 10 technologies noted by survey respondents as being used for the disinfection of private water supplies were selected for inclusion in subsequent project stages. These are as follows:

1. Hypochlorite solutions, incorporating calcium hypochlorite solution/tablets/powder and sodium hypochlorite solution

2. Hypochlorite solution, generated by onsite electrolysis of brine (OSE)

3. Chlorine gas

4. Chlorine dioxide

5. Chloramines

6. Ozone

7. Hydrogen peroxide

8. Ultraviolet (UV) irradiation

9. Reverse Osmosis

10. Ceramic Candle Filters (CCFs)

The two most-widespread technologies for disinfection of private water supplies were UV irradiation and hypochlorite, mentioned as being in use in respectively 77% and 41% of local authority areas across both surveys. Chlorine dioxide was in use in 12% of local authority areas, while the seven remaining technologies - hypochlorite generated by onsite electrolysis of brine (OSE), chlorine gas, chloramines, ozone, hydrogen peroxide, reverse osmosis and ceramic candle filters (CCFs) - were in use in ≤8% of areas.

CCFs were installed as the sole form of disinfection on private water supplies within three local authority areas. In two of these local authority areas, samples treated by CCFs had failed water quality regulations, which raises concerns about the use of this method as a sole treatment/disinfection step on private water supplies.

A wide variety of activities using private water supplies were mentioned by survey respondents; the three commonest categories being types of accommodation, tenanted properties let on a commercial basis and businesses selling food and drink.

Responses from four municipal water supply companies highlighted that care homes and hospitals are likely to practice onsite disinfection of public water supplies, using technologies including reverse osmosis, chlorine dioxide and hydrogen peroxide dosing.

7.1.3 Multi criteria analysis (MCA) of disinfection technologies used in England and Wales

Six criteria were used in the final MCA: operational cost, ease of asset management, disinfection byproducts (DBPs), efficacy against microorganisms (split into three sub-criteria, relating to bacteria, protozoa and viruses), footprint and health and safety. The highest weighting of 0.45 (0.15 for each sub-criterion) was given to microbial efficacy, reflecting its critical importance for public health.

Hypochlorite solution was the highest ranked disinfection technology, primarily due to its strong scores in microbial efficacy, operational cost, and ease of asset management. However, this chemical can result in relatively high concentrations of DBPs. UV irradiation ranked second. It performed well across multiple criteria but with relatively high operational costs and asset management challenges.

Chlorine dioxide, reverse osmosis, ozone, and chlorine gas were all regarded as effective disinfectants, but their overall ranking was lower than UV irradiation and hypochlorite because they performed comparatively poorer for certain criteria, such as ‘ease of asset management’.

Chloramines and CCFs were the lowest ranked technologies, reflecting their relatively low scores under ‘microbial efficacy’. The MCA outcome indicates both technologies are best suited as supplements to other disinfection technologies, rather than as a primary disinfectant.

7.1.4 Disinfection technologies used overseas

The suitability of physical, chemical, thermal, solar and combination treatment approaches used overseas were assessed as potential disinfection methods for use in England and Wales. Of these, ultrafiltration technologies, mixed oxidant solution and peracetic acid warrant further investigation. Bromine is a promising alternative to chlorine, but there are concerns over the formation of high levels of brominated DBPs.

7.2 Recommendations

- Modified risk assessment and/or guidance should be considered where CCFs or chloramines are the sole disinfectant technology for private or public water supplies in England and Wales.

- Ultrafiltration technologies, mixed oxidant solution and peracetic acid warrant further investigation before application to public and private water supplies in England and Wales.

- Clarify the potential health risks associated with bromine (including brominated DBP formation) ahead of this technology being considered for use in England and Wales.

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Appendix A Local authority surveys

A1 Local authority Survey 1

1. What is your full name?

2. What is your job title?

3. To the best of your knowledge, how many private water supplies are there within your local authority area?

4. To the best of your knowledge, which of the following disinfection technologies are used by private water supplies in your local authority area (please check all applicable technologies)?

- ☐ Sodium hypochlorite
- ☐ Calcium hypochlorite
- ☐ Chlorine gas
- ☐ Chlorine/hypochlorite generated by onsite electrolysis
- ☐ Other chlorine-based disinfectants (please provide the specific name in question 5)
- ☐ Chloramines
- ☐ Chlorine dioxide
- ☐ Ozone
- ☐ Hydrogen peroxide
- ☐ Ultraviolet (UV) irradiation
- ☐ Other (please specify in question 5)

5. If appropriate, please provide the specific name of any "Other chlorine-based disinfectants" or "Other" disinfectants used by private water supplies in your local authority area.

6. To the best of your knowledge, which of the following types of activities use private water supplies in your local authority area?

- ☐ Hospitals, medical centres, and other healthcare settings
- ☐ Prisons and other detention centres
- ☐ Military bases
- ☐ Educational facilities, including schools and universities
- ☐ Types of accommodation, including hotels, holiday let accommodation, inns, caravan sites and campsites
- ☐ Businesses selling food and drink, including cafes, pubs and restaurants

- ☐ Exhibitions, including art galleries, museums and conference centres
- ☐ Leisure activities, including sports stadia, leisure centres, gyms, nightclubs, theatres, ice rinks, cinemas, historic buildings
- ☐ Temporary events, such as festivals and wedding venues
- ☐ Food production and manufacture
- ☐ Tenanted properties let on a commercial basis
- ☐ Distilleries
- ☐ Maltsters and breweries
- ☐ Soft drink production
- ☐ Other (please specify in question 7)

7. If appropriate, please provide the name of any "Other" activities using private water supplies in your local authority area.

8. Would you be willing to provide more information about the disinfection technologies used by private water supplies in your local authority area in subsequent stages of the project?

9. Please provide any other information you think might be relevant in the context of this project.

A2 Local authority Survey 2

1. What is your full name?

2. What is your email address?

3. What is your job title?

4. What is the name of your local authority?

5. To the best of your knowledge, how many private water supplies are there within your local authority area?

6. To the best of your knowledge, which of the following disinfection technologies are used by private water supplies in your local authority area (please check all applicable technologies)?

- ☐ Sodium hypochlorite
- ☐ Calcium hypochlorite
- ☐ Chlorine gas
- ☐ Chlorine/hypochlorite generated by onsite electrolysis
- ☐ Other chlorine-based disinfectants (please provide the specific name in question 7)
- ☐ Chloramines

- ☐ Chlorine dioxide
- ☐ Ozone
- ☐ Hydrogen peroxide
- ☐ Ultraviolet (UV) irradiation
- ☐ Other (please specify in question 7)

7. If appropriate, please provide the specific name of any "Other chlorine-based disinfectants" or "Other" disinfectants used by private water supplies in your local authority area.

8. To the best of your knowledge, which of the following types of activities use private water supplies in your local authority area?

- ☐ Hospitals, medical centres, and other healthcare settings
- ☐ Prisons and other detention centres
- ☐ Military bases
- ☐ Educational facilities, including schools and universities
- ☐ Types of accommodation, including hotels, holiday let accommodation, inns, caravan sites and campsites
- ☐ Businesses selling food and drink, including cafes, pubs and restaurants
- ☐ Exhibitions, including art galleries, museums and conference centres
- ☐ Leisure activities, including sports stadia, leisure centres, gyms, nightclubs, theatres, ice rinks, cinemas, historic buildings
- ☐ Temporary events, such as festivals and wedding venues
- ☐ Food production and manufacture
- ☐ Tenanted properties let on a commercial basis
- ☐ Distilleries
- ☐ Maltsters and breweries
- ☐ Soft drink production
- ☐ Other (please specify in question 9)

9. In relation to question 8, please provide the specific names of any "Other" activities using private water supplies in your local authority area?

10. Would you be willing to provide more information about the disinfection technologies used by private water supplies in your local authority area in subsequent stages of the project?

11. Please provide any other information you think might be relevant in the context of this project.

Appendix B Respondents to Survey 2

Table B.1 Full list of local authority respondents to Survey 2

Number	Local authority name	Number	Local authority name	Number	Local authority name
1	Ashfield	38	Great Yarmouth	75	Windsor and Maidenhead
2	Ashford	39	Guildford	76	Sevenoaks
3	Babergh	40	Hackney	77	Shropshire
4	Barking and Dagenham	41	Haringey	78	Slough
5	Basingstoke and Deane	42	Hartlepool	79	Solihull
6	Bath and North East Somerset	43	Havering	80	Somerset
7	Blackburn with Darwen	44	High Peak	81	South Cambridgeshire
8	Boston	45	Huntingdonshire	82	South Derbyshire
9	Braintree	46	Isle of Wight	83	South Holland
10	Bradford	47	Isles of Scilly	84	South Kesteven
11	Broxbourne	48	Islington	85	Southend-on-Sea
12	Burnley	49	Knowsley	86	Stevenage
13	Calderdale	50	Lancaster	87	Stoke-on-Trent
14	Cambridge	51	Lewes	88	Swale
15	Cannock Chase	52	Maidstone	89	Swindon
16	Carmarthenshire	53	Maldon	90	Telford and Wrekin
17	Ceredigion	54	Medway	91	Tendring
18	Charnwood	55	Merthyr Tydfil	92	Torbay
19	City of London	56	Mid Sussex	93	Torridge
20	Colchester	57	Milton Keynes	94	Trafford
21	Cornwall	58	Monmouthshire	95	Tunbridge Wells
22	Cumberland	59	Newark and Sherwood	96	Uttlesford
23	Darlington	60	Newham	97	Vale of Glamorgan
24	Dartford	61	Newport	98	Wakefield

Number	Local authority name	Number	Local authority name	Number	Local authority name
25	Dorset	62	North West Leicestershire	99	Waverley
26	Dover	63	North Yorkshire	100	West Lindsey
27	Dudley	64	Northumberland	101	West Northamptonshire
28	East Devon	65	Nottingham	102	West Suffolk
29	East Hampshire	66	Oadby and Wigston	103	Westmorland and Furness
30	East Riding of Yorkshire	67	Oldham	104	Wigan
31	East Suffolk	68	Pembrokeshire	105	Winchester
32	Eastleigh	69	Pendle	106	Wirral
33	Elmbridge	70	Peterborough	107	Worcester
34	Epping Forest	71	Powys	108	Wrexham
35	Exeter	72	Preston	109	Wyre
36	Gedling	73	Redcar and Cleveland	110	York
37	Gravesham	74	Rhondda Cynon Taf		