Corrected Proof

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A 10-year critical review on hydrogen peroxide as a disinfectant: could it be an alternative for household water treatment?

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ABSTRACT

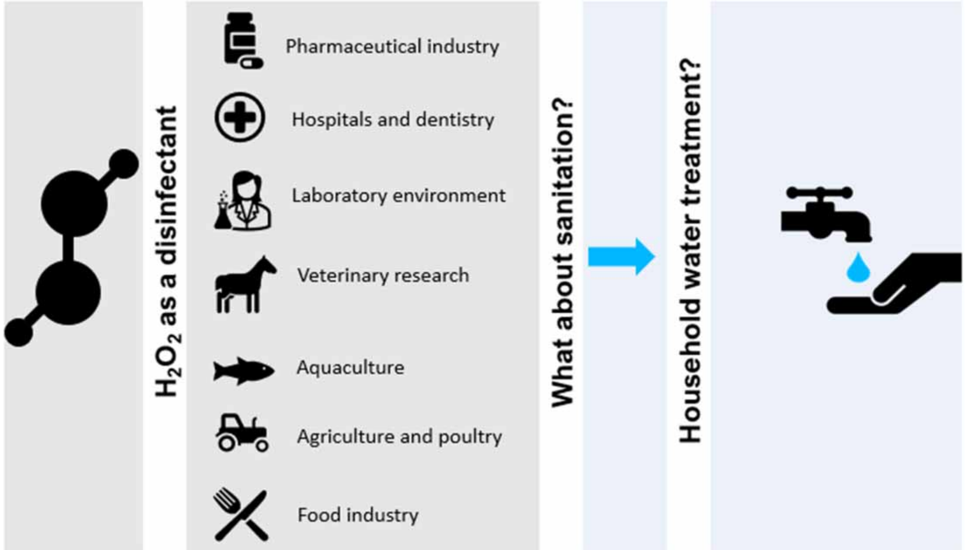
Considering that a large fraction of the global population relies on self-supplied drinking water systems, household water treatment (HWT) technologies may assist achieving the United Nations' Sustainable Development Goal 6.1, which aims at safe drinking water for all by 2030. Hydrogen peroxide disinfection has been widely known as an effective approach for microorganism inactivation, however, it has not been much explored as a standalone solution in sanitation. In this sense, this review presents systematically organized information extracted from papers on H_2O_2 disinfection from 2011 to 2021. Filtered data was analyzed by content and network visualization, raising a discussion on whether H_2O_2 could be a potential HWT intervention, and which limitations and prospects are there for its research and implementation. In short, we found a lack of consistency in operational conditions, as most of the retrieved studies address individual use of H_2O_2 as control to combined treatments. Additionally, oxidant demand and kinetics considering local water quality are lacking, as well as information on residual neutralization, toxicity, and up-scaling. This critical review reveals gaps that encourage further research tackling different disinfection challenges, so that this alternative can be evaluated for implementation as an HWT technology, particularly at context-specific situations.

Key words: alternative disinfection, decontamination, peroxidation, point-of-use, SDG 6

HIGHLIGHTS

- Though widely applied in decontamination, H_2O_2 is not popular in water disinfection.
- Retrieved records do not include data on H_2O_2 as an HWT.
- Operational conditions found for liquid H_2O_2 use often favor catalytic treatments.
- Context-specific studies are recommended to evaluate HWT feasibility.

GRAPHICAL ABSTRACT



INTRODUCTION AND BACKGROUND

Inequalities in access to safe drinking water remain a current challenge, even though there has been improvement at a global scale (UNICEF & WHO 2019; Price *et al.* 2021). In most low-income countries, water quality compliance is insufficient because of a lack of commitment in supply infrastructure, leading to poor access to potable water (Okoro *et al.* 2021). While policymakers are in search of long-term solutions to water insecurity, a recent meta-ethnographic synthesis has identified that some of the coping strategies could be as simple as providing purification of water prior to consumption (Achore *et al.* 2020). In fact, a large fraction of the global population relies on small supply systems (Debiasi & Benetti 2019), in the form of wells, boreholes or harvested rainwater usually owned and maintained by individual families (Foster *et al.* 2021).

In this sense, plain decontamination solutions would be effective and desirable interventions (Patil *et al.* 2020) for providing safe drinking water in households. When locally applied, these are known as household water treatment (HWT) systems and could be employed as point-of-use (POU) or point-of-entry (POE) technologies, which can play a strategic role to help meeting households' immediate water needs (Pooi & Ng 2018) and, thus, overcome inequalities.

There are different approaches for HWT, which vary from portable devices (Montenegro-Ayo *et al.* 2020; Patil *et al.* 2020) to in-home installed systems, e.g., photovoltaic powered ultraviolet and visible light-emitting diodes (Lui *et al.* 2014), household slow sand filters (Freitas *et al.* 2022), etc. Other examples of decentralized treatment schemes rely on even simpler interventions, such as chlorination, which has been used in disinfection since the early 1900s (USEPA 1999).

As much as conventional treatments, HWT technologies also face emerging challenges. Chlorination, for instance, which is a widely spread POU method (Mitro *et al.* 2019; Clayton Thorn & Reynolds 2021), is associated to the formation of toxic disinfection by-products (DBPs) (Hu *et al.* 2018; Leite *et al.* 2022). Hydrogen peroxide, comparatively, is considered as a cleaner substance, as it is usually decomposed into oxygen and water, avoiding the DBP formation upon successful disinfection (Farinelli *et al.* 2021; Herraiz-Carboné *et al.* 2021). In fact, H_2O_2 is an alternative oxidant for controlling the generation of by-products (Poleneni 2020), rising as a promising candidate for HWT applications (Silva *et al.* 2021). In addition, H_2O_2 has been employed in addressing other challenges in disinfection, as in inactivation of antibiotic resistant (AR) microorganisms (Cadnum *et al.* 2015; McKew *et al.* 2021), as well as pathogenic protozoa, known to be resistant to conventional disinfection (Quilez *et al.* 2005; Liang & Keeley 2012).

Although recent research has explored some advantages and constraints of H_2O_2 as a potential HWT by conducting a laboratory scale experiment (Silva & Sabogal-Paz 2021), to our knowledge, literature lacks current and systematically organized information in that regard. Therefore, this critical review aimed to provide an overview of the applications of hydrogen peroxide in the last decade and use this data to shed light onto H_2O_2 as an alternative for water disinfection at the household level, that is, a strategy to tackle inequalities in access to safe water.

METHODS

The main research question here was: 'could hydrogen peroxide be used as a water disinfectant at the household level?' In order to answer it, a literature review on H_2O_2 disinfection was performed, so that trends and gaps could be identified through qualitative synthesis and a critical discussion.

Research strategy and data curation

The research strategy was an adaptation of the PRISMA model (Preferred Reporting Items for Systematic Reviews and Meta-analyses) (Liberati *et al.* 2009). Articles were identified from the Scopus database, restricting documents from 2011 to 2021 using 'hydrogen peroxide disinfection' as keywords (with Boolean descriptors: 'hydrogen AND peroxide AND disinfection').

From the total retrieved results, papers that utilized plasma treatment, foam, and cleaning wipes were removed in screening at the title and abstract levels. Combined and catalytic treatments were also dismissed, as well as electrogeneration, because these involve more parameters than individual applications do, thus exceeding the scope of our present discussion. Studies on decontamination of medical, as well as personal protection equipment (PPE) were not considered, as most of these publications were context-oriented within specific healthcare applications or emergencies (such as the COVID-19 pandemic). Review articles were also excluded.

Independent extraction of eligible articles was carried out using predefined data filters including purpose/context (e.g., decontamination, agriculture, aquaculture, sanitation, etc.), matrix (surface, water, wastewater, etc.), target organism, method of application, main parameters, and relevant notes. At this level of screening, air disinfection was removed from eligible papers, as well as decontamination of tissue and vaccine industry applications, which were only identified after data extraction.

The final qualitative synthesis included studies narrowed to the sanitation field. Even so, obtained information from the remaining eligible articles was still integrated as scope for discussion in this critical review, as well as general data visualization.

Data visualization

Filtered information from selected articles was organized into networks built on Cytoscape (Shannon *et al.* 2003) for a broader visualization. All of the additional references from extracted data, as well as detailed information are listed in Table S1, available in the supplementary file.

RESULTS AND DISCUSSION

A flowchart of the number of records from each phase of the research strategy is shown in Figure 1. From those, only 1% of publications were from the sanitation field. Although this result may be influenced by a supposed increase in pandemic-related titles (retrieved in the identification phase), it still indicates a lack of research in H_2O_2 standalone disinfection of water and wastewater.

Overview of hydrogen peroxide disinfection

Despite we found it to be unpopular as a standalone disinfectant in sanitation, hydrogen peroxide is a widely known disinfectant and biocide, having different modes of action, which rely on intra and extracellular effects, as well as inhibition of peroxide activity and internal Fenton process (Maillard 2002).

Figures 2 and 3 display networks built out of data extracted from the 142 selected papers ($n = 16$ in sanitation; $n = 126$ from other applications, details in the supplementary material). Density of connections indicates the frequency in which such relationships are present in retrieved documents.

Figure 2 illustrates different scenarios where H_2O_2 has been applied and the methods by which it was applicated. By observing the network, it is possible to identify that the main method of H_2O_2 application was found to be through liquid and vapor (i.e., fog), but it has also been used as liquid applied as spray, and aerosol (i.e., dry mist). In sanitation, hydrogen peroxide has been reported in uses only as a liquid, mainly pure but also with peroxygen-based disinfectant formulas.

It should be noted that depending on the application form, different operational conditions apply. Vaporized hydrogen peroxide (VHP) systems often generate vapor by adding $> 30\%$ H_2O_2 solutions to a vaporizer to be heated at 130 °C and then produce vapor that is aimed to condense onto surfaces (Otter *et al.* 2010; Holmdahl *et al.* 2011). Aerosol systems (AHP) rely on pressure to produce aerosols with a particular particle size and often include lower H_2O_2 concentrations and mixtures of

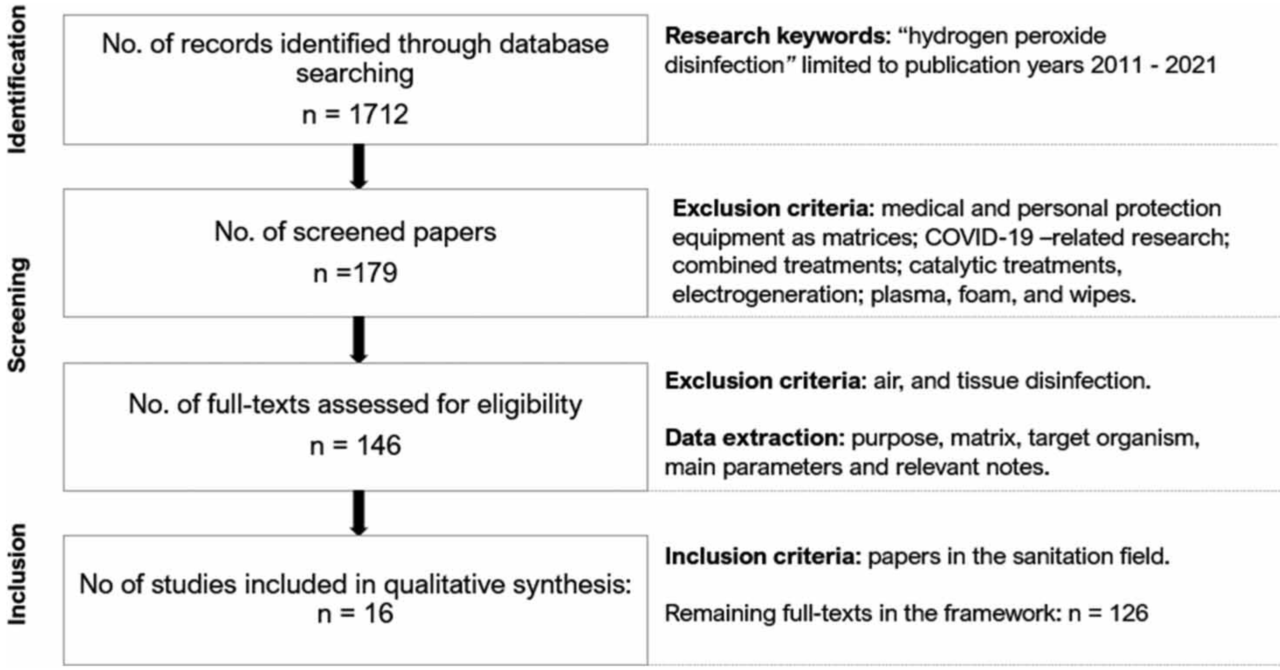


Figure 1 | Flow of information through different phases of the systematic review of H_2O_2 disinfection.

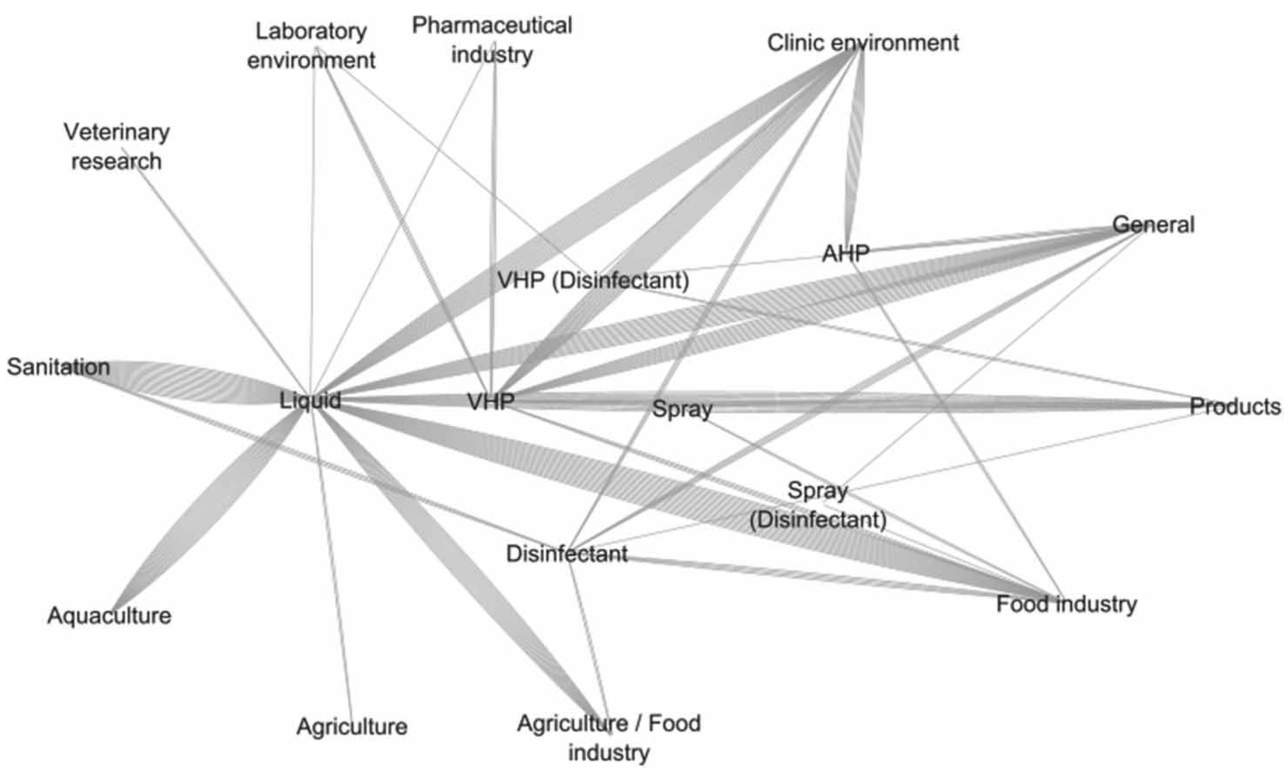


Figure 2 | Network of the main areas of hydrogen disinfection research and forms of application (2011–2021). Notes: AHP = aerosolized hydrogen peroxide. General = decontamination of room or in-house environments. NA = not available information. Disinfectant = peroxygen-based products that may contain a small percentage of other substances (e.g., alcohol, peracetic acid, silver nitrate, quaternary ammonium, etc.). VHP = vaporized hydrogen peroxide.

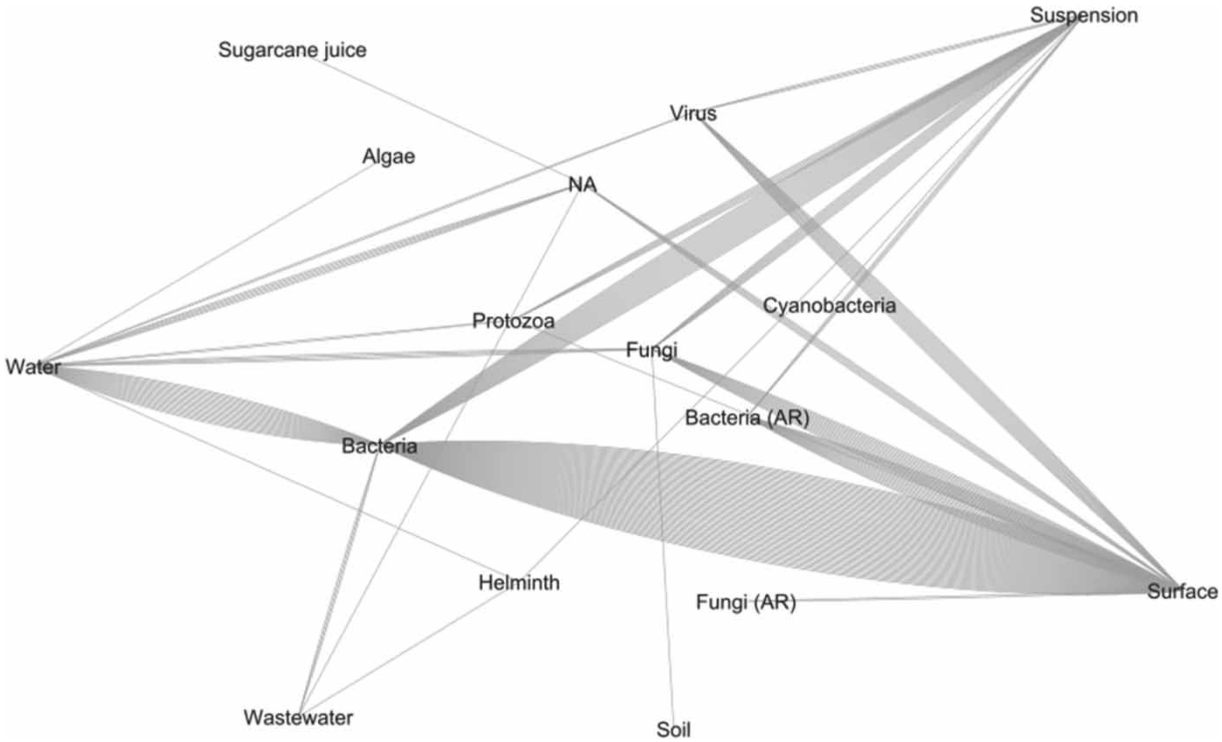


Figure 3 | Network of retrieved information of matrices and target-organisms in hydrogen disinfection research (2011–2021). Notes: AR = antibiotic/antifungal resistant. NA = not available.

silver cations, for instance (Holmdahl *et al.* 2011). This variety in application form indicate a certain versatility of hydrogen peroxide as a disinfectant but must be carefully considering when determining working conditions for different field uses.

Figure 3 shows a network illustrating the decontamination matrices found in H_2O_2 disinfection research, as well as the main target-organism groups. Most research is focused on surface decontamination, but there are liquid matrices relevant to sanitation as in water and wastewater. Details of disinfection settings are present in Table S1 in the supplementary material.

Overall, a wide range of target-organisms was found for H_2O_2 disinfection, but the main targets were bacteria, regardless of the matrix. In clinic environments, particularly, these even include antibiotic resistant (AR) bacteria such as methicillin-resistant *Staphylococcus aureus* (MRSA), and vancomycin-resistant *Enterococcus* (VRE) (Cadnum *et al.* 2015; Amaeze *et al.* 2020). Other groups of microorganisms have also been explored, as viruses and fungi. The latter should be highlighted, as there is research on H_2O_2 applied against emerging threats to public health like the fungus *Candida auris* (Cadnum *et al.* 2015; Cobrado *et al.* 2021; McKew *et al.* 2021). Details of targeted microorganism groups and their references are available in the supplementary material.

H_2O_2 in sanitation research

In sanitation, the main applications observed were related to microorganism inactivation per se, as laid out in Table 1. Target-organisms were often from bacteria groups (especially fecal contamination indicators, e.g., *Escherichia coli*), but there were also studies contemplating protozoan (oo)cysts and helminth eggs. *Giardia* spp. and *Cryptosporidium* spp. are particularly relevant parasites for studies on technologies to be applied at the household level, because their infective forms are resistant to conventional disinfection, they are associated to worldwide diseases outbreaks (Efstratiou *et al.* 2017), and have been recently reported in water sources in rural regions, including both surface and groundwater (Chuah *et al.* 2016; Chique *et al.* 2020; Kifleyohannes & Robertson 2020). Helminth eggs are not only appropriate targets due to their resistance to disinfection, but also because they are considered social indicators of a country (Guadagnini *et al.* 2013), thus directly relevant to future studies on HWTs. Less attention was directed to cyanobacteria, viruses, and fungi, but they were still present, and point to pertinent targets for further and directed research.

Table 1 | Summary of aims and targets of research on hydrogen peroxide disinfection in sanitation (2011–2021)

Main purpose	Target	Relevance	Microorganism group	Reference
Validate viability assessment protocol	*Cryptosporidium parvum*	Resistant pathogen	Protozoa	Liang & Keeley (2012)
Inactivation	*Ascaris suum* eggs	Resistant pathogen	Helminth	Morales *et al.* (2013)
Inactivation	TC, *Escherichia coli*; *Ascaris* spp. eggs	Resistant pathogen	Bacteria; helminth	Guadagnini *et al.* (2013)
Inactivation	*E. coli*	Indicator	Bacteria	Patil *et al.* (2013)
Kinetics and effects of pH	TC, *E. coli*	Indicator	Bacteria	Vargas *et al.* (2013)
Inactivation	*Giardia duodenalis*	Resistant pathogen	Protozoa	Guimarães *et al.* (2015)
Inactivation	TC, *E. coli, Staphylococcus aureus, Salmonella* spp., *Shigella* spp.	Field study	Bacteria	Mohammed (2016)
Monitor shifts in microbial communities	General bacteria profiling	Complex matrix	Bacteria	Yang *et al.* (2017)
Inactivation	Algae; *E. coli*	Complex matrix	Algae; bacteria	Farinelli *et al.* (2021)
Inactivation	*Hymenolepis nana* egg	Resistant pathogen	Helminth	Landry *et al.* (2021)
Inactivation	*E. coli*; Phi X174	Indicator	Bacteria; virus	Silva & Sabogal-Paz (2021)
Inactivation; toxin removal[a]	*Microcystis aeruginosa*	Complex matrix	Cyanobacteria	Fan *et al.* (2014)
Removal of organic matter[a]	N/A	Complex matrix	N/A	Alcalá-Delgado *et al.* (2018)
Dechlorination[a]	N/A	Quenching agent	N/A	Qian *et al.* (2015)
Inactivation[b]	*Legionella pneumophila*	Biofilm	Bacteria	Farhat *et al.* (2011)
Inactivation[b]	*Verticillium dahliae*	Field study	Fungi	Santos-Rufo & Rodríguez-Jurado (2016)

Notes: [a]Oxidation experiments. [b]Study applied a peroxygen-based disinfectant. TC = total coliforms. N/A = does not apply.

HWT research has shown that added H_2O_2 may be promising with solar light and Fenton processes, producing fast killing effects in resilient microbial contaminants like fungi spores (Sichel *et al.* 2009), and virus (Ortega-Gómez *et al.* 2015). Hydrogen peroxide-assisted pasteurization was also effective against *E. coli* and bacteriophage (Sammarro Silva *et al.* 2022). These and similar articles were not included in this review because they refer to combined treatments, but definitely showcase potentials of hydrogen peroxide in household applications.

But as for standalone H_2O_2 in households, a knowledge gap (Jacobs 2011) was found. From retrieved documents in the sanitation context, only one study aimed at POU water treatment. Silva & Sabogal-Paz (2021) explored liquid H_2O_2 as a potential HWT, benchmarking it against chlorine for the inactivation of indicator bacteria and a virus contamination model, as described in Table 1. This research, however, highlighted the need for site-specific information, including a broader assessment that includes different microorganism groups. This point has also been raised in a commentary (Mraz *et al.* 2021) that illustrated that decisions regarding water and sanitation should not only rely on indicators, but also include pathogens. That was demonstrated considering calculated probabilities of infection risk, which are significantly higher when inactivation information for pathogens is included. In order to illustrate a water treatment setting, Mraz *et al.* (2021) considered chlorination of surface water. We believe an analogous situation would apply to H_2O_2 as an HWT, thus inviting further research to describe whether interventions are realistic for each contamination scenario.

Operational conditions in sanitation studies

In order to shed light onto conditions in which non-catalyzed oxidation with H_2O_2 may be applied for water treatment, details of peroxidation within the scope of sanitation in the last decade are present in Table 2.

We believe there is some bias regarding the idea of hydrogen peroxide to be inefficient in the sanitation field because only few studies investigate disinfection with different methods by employing equivalent biocidal efficiency levels. Yang *et al.* (2017) has done so to compare the effects of monochloramine and hydrogen peroxide on the biological community of treated wastewater and found that minimum inhibitory concentration of the former (0.7 mg/L) was ten times lower than H_2O_2 (7 mg/L), using *Pseudomonas aeruginosa* as a contamination model. Authors still raise the discussion that lab-cultured *P. aeruginosa* may respond differently from a strain native to wastewater, as well as from other organisms present in environmental matrices (Linley *et al.* 2012; Yang *et al.* 2017).

Additionally, several works on combined and catalytic treatment, for instance, apply H_2O_2 alone as a control, hence its low doses may reflect on ineffective results. A study that compared hydrogen peroxide to a Fenton-type nanocatalyst (Morales *et al.* 2013), for example, selected a dose of 28.64 mg/L H_2O_2 based on the optimal Fe:H_2O_2 ratio (Di Palma *et al.* 2003). Similarly, another work incorporated in Table 2 applied the 30 mg/L dose for a hydrogen peroxide oxidation, when it was, in fact, a control experiment to describe enhanced performance of H_2O_2/UV on disinfecting wastewater. Similarly, a control study in contrast to galvanic Fenton (GF) treatment investigated sole hydrogen peroxide by applying a 7,840 mg/L H_2O_2 dose on industrial wastewater at pH 2.8, also following the Fe:H_2O_2, in this case, optimal for GF (Alcalá-Delgado *et al.* 2018), also highlighting the variety in working conditions for hydrogen peroxide as a disinfectant. Although these papers prove a point in terms of possible synergism, their conclusions should not be escalated to hydrogen peroxide efficiency itself, which has been known as satisfactory, as long as adequate operational conditions apply. These have been found to vary a lot according to specific challenges such as matrix or target-organism.

Here, it is recommended that if H_2O_2 is investigated for HWT uses, benchmarking other treatments should consider equivalent working conditions in terms of biocidal efficiency, particularly because the mode of action of each technology is not the same. Catalytic treatments rely on the formation of superoxide and hydroxyl radicals, which are highly reactive, thus, easily, and rapidly able to oxidize a wider range of molecules and recalcitrant pollutants. That said, catalytic processes are attractive for removing toxins, for instance (Mansouri *et al.* 2019), as well as resistant pathogens (Abeledo-Lameiro *et al.* 2017), as described by peer literature. Nevertheless, such challenging purposes may not necessarily be the goal of liquid H_2O_2 as a HWT (e.g., in replacement of in-house chlorination), which should often target fecal bacteria and similar threats considering the water source, ideally with high quality. Additionally, HWTs are aimed to be low-cost and user-friendly, which are not necessarily the case of, for example, Fenton processes, that require a narrow acid pH range, and their iron lost to acidic sludge may be a hazardous waste (Garrido-Ramírez *et al.* 2010).

Depending on the source water, it is possible that non-catalyzed hydrogen peroxide disinfection benefits from the presence of metallic ions present in the matrix, as previously reported for treated sewage (Vargas *et al.* 2013). Contrariwise, the presence of carbonates and bicarbonates, which is frequent in groundwater, could hamper oxidation, as described by a research on H_2O_2 as a POU disinfectant that used water from a local well, considering this it is a common supply source in low-income regions (Patil *et al.* 2013). This illustrates the importance of properly characterizing the water source and context when designing an HWT (Silva *et al.* 2021), whether it relies on non-catalyzed H_2O_2 or not, because factors such as pH, organic matter, and the presence of ions may lead to either synergistic or antagonistic effects on microbial inactivation. Few studies on kinetics of peroxidation aimed at disinfection are reported in literature, as previously stated by peers (Vargas *et al.* 2013), and confirmed by our review. Kinetic constants are expected to vary according to the contamination scenario, as well as working conditions.

The same applies to exposure time, which varies depending on the treatment's purpose (e.g., shock disinfection, conventional disinfection, challenging matrices, etc.). From our literature analysis, and as displayed by Table 2, exposure times varied from seconds to days, not necessarily presenting an equivalent change in the order of magnitude of the H_2O_2 concentration under test. This makes sense when considering short and long-term effects, but does not necessarily indicate efficiency or feasibility of a project, which should be discussed in future work for HWT. Moreover, few papers evaluate disinfectant demand prior to selecting contact time. This gap emphasizes the importance of the investigation of inactivation kinetics and residual disinfectant decay to assist the proposal of proper H_2O_2-based technologies, considering local particularities. A study on cell viability of cyanobacteria and toxin removal by different oxidants performed a disinfectant demand

Table 2 | Operational details of disinfection experiments using H_2O_2 in sanitation (2011–2021)

Scale	Matrix		Operational parameters	Quencher	Reference
Bench (batch)	Suspension		28.64 mg/L for 58 min	Sodium thiosulfate	Morales *et al.* (2013)
			15, 60, and 6,000 mg/L for 5.5 s, 60 and 30 min, respectively	NA	Guimarães *et al.* (2015)
	W	Artificially contaminated surface and disinfected water	0.10, 0.60, 1, 3, 6, 10, 20 and 30% for 1 h. Kinetic tests: 0.1, 0.6 and 3% for 36 h, sampled at various time points (1, 2, 4, 6, 8, 12, 16, 24, 30 and 36 h)	None[a]	Liang & Keeley (2012)
		Artificially contaminated groundwater	10, 100, 1,000 and 10,000 mg/L inactivation for 10, 30, 60, and 120 min	None[b]	Patil *et al.* (2013)
		Drinking water for cattle	25, 35, and 40 mg/L from 12 to 24 h	NA	Mohammed (2016)
		Groundwater contaminated with receiving leachate	0–15 mM for 2 h	NA	Farinelli *et al.* (2021)
		Microcosm containing helminth eggs recovered from wastewater and fecal sludge	0.1 cl/L, 0.2 cl/L, 0.3 cl/L, 0.4 cl/L, 0.5 cl/L and 0.6 cl/L for 24 h	None[c]	Landry *et al.* (2021)
		Artificially contaminated test water	0.01, 0.03, 0.05, 0.1, 0.3 and 3% for 30 min; 3% for 60 min	Sodium metabisulfite	Silva & Sabogal-Paz (2021)
	WW	Treated sewage; artificially contaminated synthetic WW	0–300 mg/L for 10 min. Kinetic tests: 25, 50, 75 and 100 mg/L. Aliquots sampled at various time points until 60 min	NA	Vargas *et al.* (2013)
		Artificially contaminated treated sewage	Initial doses: 0.0, 10.2, 30.6, and 51 mg/L. Exposure time: 2 days	Sodium thiosulfate	Fan *et al.* (2014)
		Treated sewage	7 mg/L for 10 and 60 min	None[a]	Yang *et al.* (2017)
		Industrial	7,840 mg/L was dosed at 1, 5, 10, and 15 min during a treatment time of 120 min. pH: 2.8.	NA	Alcalá-Delgado *et al.* (2018)
		Treated sewage	30 mg/L. NA exposure time.	NA	Guadagnini *et al.* (2013)
Bench; pilot (batch)	W	Suspension; Artificially contaminated surface water for irrigation	In-vitro experiments: 0.2, 0.8, 3.2, 12.8- and 51.2 mL/L OX-VIRIN®; 5.2, 15.5, 46.4, 139.2, and 417.5 μL/L OX-AGUA AL 25®. Exposure times: 1 min, 5, 15, and 30 days. Natural conditions: 0.8 and 3.2 mL/L OX-VIRIN®; 46.4 mL/L OX- AGUA AL 25®. Exposure times: 0, 7, 14, and 18 days after infestation.	Sodium thiosulfate	Santos-Rufo & Rodríguez-Jurado (2016)
Pilot (flow-through)	W	Hot water flowing through biofilm	1,000 mg/L at a 20 mL/min flow for 3–6 h	None[d]	Farhat *et al.* (2011)

Notes: [a]Washing with PBS followed by centrifugation. [b]Considers complete dissolution of hydrogen peroxide residuals. [c]Washing with distilled water followed by centrifugation. [d]The total volume of treated water was renewed until residuals could not be detected. NA = not available information. W = water. WW = wastewater. Peroxygen-based commercial disinfectants: OX-VIRIN® = 25% H_2O_2 plus 5% peracetic acid and 8% acetic acid; OX-AGUA AL 25® = 5% H_2O_2 plus 25% alkyl dimethyl benzyl ammonium chloride.

experimental screening and determined chlorine acts in a matter of 30 min to get effective results, whereas ozone takes 5 min, potassium permanganate requires 180 min, and hydrogen peroxide could demand almost 2 days (Fan *et al.* 2014). This type of information would allow properly assessing costs and boost the design of household devices and their efficiency, as well as proportionally compare performance to other technologies currently available.

Target-organisms also play an important role when determining operational conditions. In the food industry, surface disinfection should consider the combination of contact time and concentration that considers the most resistant contaminant, in agreement with a 'worst case scenario approach' (Visconti *et al.* 2021). We believe this notion also applies to household water treatment, which endorses the need for kinetic experiments, as well as an investigation of a diverse range of microorganisms, including resistant pathogens prior to any intervention, particularly when working with complex contaminated matrices, which may require larger biocidal concentrations to target persistent/surviving microorganisms (Farinelli *et al.* 2021).

It should be pointed out, additionally, that there is a lack of standardization in units of measure regarding H_2O_2 dosing, which we decided to present verbatim in Table 2. Even within the sanitation field, some papers report mg/L, while others treat it as cL/L, mmol/L and % (v/v or w/v). The latter is the most common approach found when screening eligible papers for this research (considering various decontamination scenarios). Although units can be easily converted, this variety may cause misinterpretations at first glance. Here, we recommend the use of % (v/v or w/v) in future research regarding non-catalyzed H_2O_2 in HWT, as it could simplify the understanding of dilutions from the users' perspective, especially because commercial hydrogen peroxide is often available as such.

Quenching

Residual H_2O_2 activity will determine the need for quenching. For drinking water purposes, regulation sources do not include standards for residual concentration, supposedly because H_2O_2 is not a conventional disinfectant in water treatment utilities (i.e., it has not been mentioned in classic guidance manuals such as USEPA (1999)). Such documents provide technical data and engineering information aimed at full-scale drinking water treatment plants, hence not applying to HWT systems conception, to which quenching may still be a concern.

As for food decontamination, comparatively, H_2O_2 appears in the tolerance exemptions list from USEPA (2002) on all commodities at the rate of $\leq$1% hydrogen peroxide per application on growing and postharvest crops. The Food and Agriculture Organization of the United Nations (FAO) along with the World Health Organization (WHO) mentions that H_2O_2 excess is destroyed after its application for bactericidal effect in dairy products and foodstuffs. Toxicological considerations, thus, apply only to possible interference in nutritional value of treated products or the formation of toxic substances, but not to residual hydrogen peroxide (FAO & WHO 1974). Treated with antimicrobial washing solutions, small residues on food at the time of consumption would not pose a safety concern (FAO & WHO 2004).

Though not present in reports by international entities of the water sector, some eco-toxicity data is provided by literature on sanitation. A study on GF treatment (Alcalá-Delgado *et al.* 2018) has found that a 40 mg/L H_2O_2 residual does not affect *Lactuca sativa* germination. However, hydrogen peroxide standalone disinfection, which led to a 1,570 mg/L residual, strongly inhibited the germination of lettuce seeds. Studies that evaluated kinetics of H_2O_2 decay in treated effluent (Fan *et al.* 2014) found that it remained relatively stable after a six-day period (a final residual of 45.7 mg/L, which is higher than the initial dose of many treatments, as described in Table 2). Such scenarios indicate that residual hydrogen peroxide must be accounted in HWT conceptualization and design, particularly considering water quality, oxidant demand and working concentrations of disinfectant, as its residual may possibly not be so small compared to antimicrobial solutions applied in food decontamination, for example.

Table 2 includes a list of quenching agents applied for neutralizing hydrogen peroxide in sanitation and illustrates how it has been explored in peer scientific work. Research on neutralization of H_2O_2 following a UV-based advanced oxidation process found that chlorine is preferred over bisulfite for neutralization of the natural water matrix under test, both reacting at a 1:1 stoichiometric ratio (Wang *et al.* 2019). As for individual use of H_2O_2 in water treatment, such detailed investigation of chemical quenching is lacking. Likewise, there are limited reports in full-scale applications that could be analogous for HWT. From our perspective, and considering gathered data, quenching should be considered as an operational parameter in HWTs, i.e., it is of major importance to determine whether the neutralizing agent is necessary, its dosing ratio and application form, so that system design is properly conceptualized and there are no risks in consumption, handling, and disposal.

Implementation challenges

Scaling from benchtop may be one of the main future challenges in implementation, even if it is at the household level, particularly because peroxidation is not a conventional method recognized by the water sector. Table 2 indicates that sanitation research using H_2O_2 have mostly relied on bench-scale studies. An assessment on chlorine as an HWT solution found that efficacy under laboratory controlled conditions was significantly better than POU chlorination, when both were evaluated on their log reductions and their ability to meet microbiological safety standards (Levy *et al.* 2014). Likewise, if H_2O_2 is to be a candidate for HWT, it is highly recommended that context-specific conditions are considered (Silva & Sabogal-Paz 2021), as previously mentioned.

Cultural particularities should be also considered at the development of the implementation strategies. This is a key gap found in our review, as there were no retrieved reports on standalone H_2O_2-based interventions at households. We believe challenges may be similar to chlorination in regard to community acceptance and follow-up. Hence, benchmarking strategies is encouraged, aiming to potentialize facilitators and avoid barriers, some of which have been reported for chlorine use (Mitro *et al.* 2019).

As for engineering aspects, authors do not consider hydrogen peroxide local storage to be a hazard (Domènech *et al.* 2001), but corrosive properties should be taken into account. Resistance to corrosion has been explored in research on plumbing materials commonly used in hospital settings (Giovanardi *et al.* 2020) and the effect of various disinfectants have also been studied on experimental coupons (Marchesi *et al.* 2016). This should also be considered for HWT applications, aiming at longer device lifespan and a design that is safe to users.

An alternative to cope with these issues, both from the public acceptance and supply infrastructure perspectives, is the implementation of H_2O_2 disinfection at community collection points or as a POE solution. This could reduce the dependance on behavior change by relying on in-line devices without requiring major infrastructure (Powers *et al.* 2021) and effort from the users. This brings opportunity for the conceptualization of automated and-or in-line hydrogen peroxide dosing mechanisms.

CONCLUDING REMARKS

The network visualization approach for a semi-quantitative analysis was an attempt to mitigate the intrinsic interpretation bias in any literature review. Gathered data indicated that H_2O_2, has not been much explored in sanitation in the last decade and has not been much investigated as a POU/POE technology, even though research in different areas point it as a promising method. This brings up a knowledge gap, despite the attention that hydrogen peroxide disinfection has so far attracted in other disciplines. The main contribution of this review was therefore to shed light onto these gaps and opportunities for experimental research and, possibly, future implementation in household water treatment considering inherent challenges.

We have found that it is difficult to find consistency in dosing and exposure time due to scarce specific literature, and because several studies on hydrogen peroxide as a disinfectant for water or wastewater treatment actually do so as a control for catalytic treatments. Additionally, matrix-specific kinetic experiments are lacking for liquid H_2O_2 alone in the sanitation sector, as well as detailed information on residual neutralization, which impedes immediate application of this disinfection solution, especially at the household level, where there is a practical knowledge gap. Hence, unexplored dimensions on working conditions of H_2O_2 as a standalone process invite exploratory research that tackle different disinfection challenges, so that this alternative could be evaluated specifically for implementation as an HWT technology.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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