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A review of physicochemical and biological contaminants in drinking water and their impacts on human health

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Abstract

Clean drinking water is one of the United Nations Sustainable Development Goals. Despite significant progress in the water purification technology, many regions still lack access to clean water. This paper provides a review of selected water contaminants and their impacts on human health. The World Health Organization (WHO) guidelines and regional standards for key contaminants were used to characterise water quality in the European Union and UK. The concept of safe drinking water was explained based on the non-observed adverse effect level, threshold concentrations for toxic chemicals, and their total daily intake. Various techniques for monitoring water contaminants and the drinking water standards from five different countries, including the UK, USA, Canada, Pakistan and India, were compared to WHO recommended guidelines. The literature on actual water quality in these regions and its potential health impacts was also discussed. Finally, the role of public water suppliers in identifying and monitoring drinking water contaminants in selected developed countries was presented as a potential guideline for developing countries. This review emphasised the need for a comprehensive understanding of water quality and its impacts on human health to ensure access to clean drinking water worldwide.

Keywords: Drinking water contaminants; Physicochemical contaminants; Biological contaminants; Human health risks; Waterborne diseases; Water quality; Public health concerns; Water treatment

1. Introduction

Water is a vital natural resource that needs to be protected from pollutants (Megersa et al., 2014; WHO, 2017; EA, 2019). Currently, only 0.5%−1.0% of the total available water resources can be regarded suitable for drinking (Yan et al., 2016; Kausley et al., 2019). The quality of water can be described in terms of physical, chemical and biological contaminants (Palansooriya et al., 2020). Generally, four types of contaminates are observed in water as shown in Fig. 1.

Looking at the situation in developing countries, nearly a half of the billion population in China lacks access to clean drinking water. This is primarily due to varying degrees of contamination that affect the majority of all the available water sources (Megersa et al., 2014). Although the consumption of water by the industrial sector occupies only 3% in India, this sector significantly contributes to water pollution (Verma et al., 2012).

In England and Wales, 32 privately-owned companies supply water to 50 million households and other consumers. The water and sewerage policies, legislation and standards are set by the Department for Environment, Food and Rural Affairs (DEFRA), following the Water Framework Directive (WFD) and World Health Organization (WHO) guidelines (Ofwat, 2021). The water service regulation authority,

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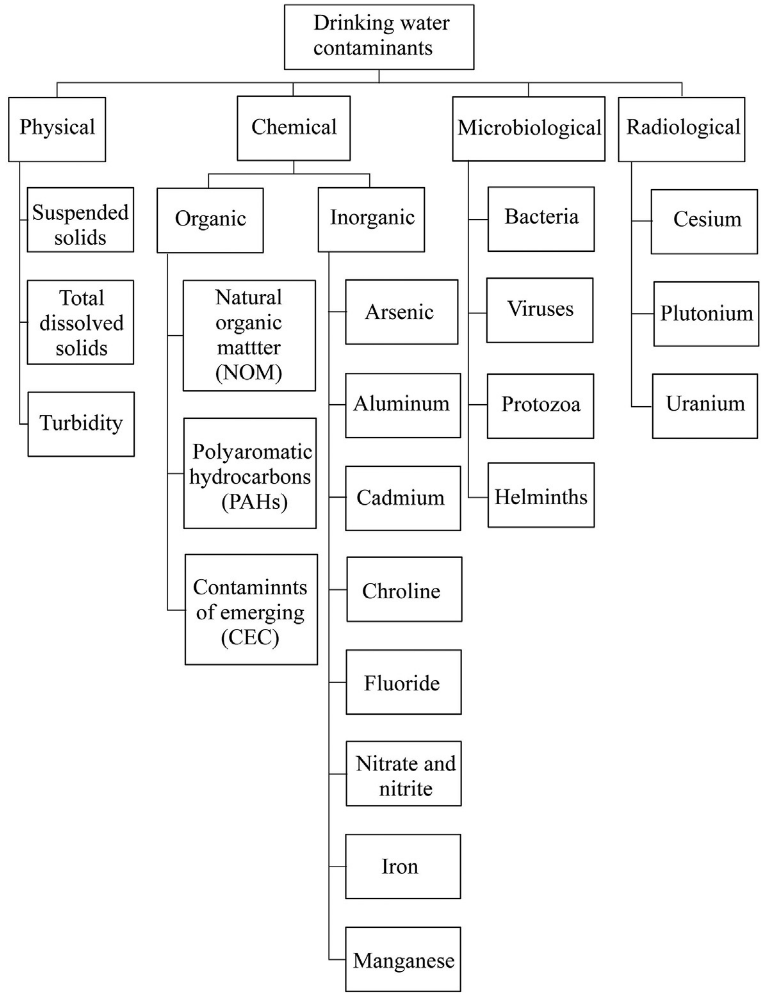

Fig. 1. Major contaminants in drinking water considered in this review.

generally referred to as Ofwat, is the economic regulator responsible for protecting the rights of consumers and regulating prices for the supplied water. The quality of the supplied drinking water is regulated and monitored by the Drinking Water Inspectorate (DWI) (Ofwat, 2021). The Water Industry Act 1991 requires that local authorities should have information about the quality and quantity of the supplied water in their respective regions (DWI, 2019).

In Scotland, the regulating body is the Drinking Water Quality Regulator (DWQR). The equivalent counterpart in Northern Ireland is the Drinking Water Inspector (inspectorate). In England, the Environment Agency (EA) is responsible for maintaining and improving the quality of water. This includes river, marine, surface and ground water in addition to water abstractions. In Scotland, Northern Ireland and Wales, the concerned bodies are the Scottish Environment Agency (SEPA), Environment and Heritage Services (EHS) and Natural Resources Wales (NRW), respectively (EA, 2019).

Within the presented frameworks, the objectives of this review are to (1) identify key contaminants in drinking water and analyse their influence on public health, (2) evaluate and contest different methods for monitoring drinking water parameters and (3) analyse the public perception of safe drinking water and compare it to WHO guidelines and standard parameters with a focus on public water supplies.

2. Methodology

2.1. Selection of key contaminants

This research was primarily based on a review of literature available on physicochemical and biological contaminants in drinking water. The first objective of the review is to characterise the major contaminants in drinking water. As the research was conducted in the UK, the key contaminants for this study were selected based on DWI reports. Reports of the public water supplies (PWS) in England and Wales for six quarters during the years 2019 and 2020 were selected. During this time, the physical, chemical and biological contaminants that repeatedly failed to comply with the standards were selected as the key contaminants for this study (Fig. 2).

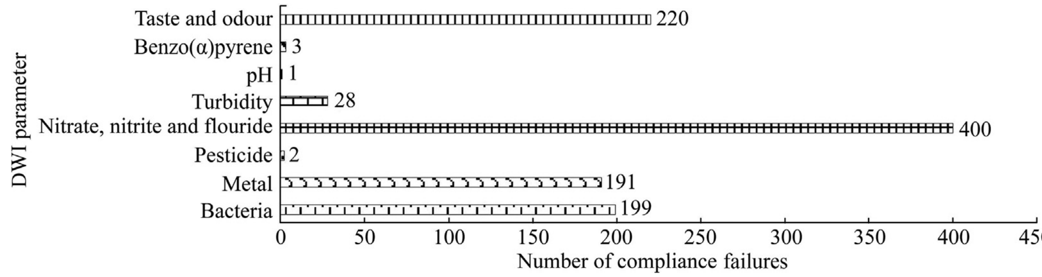

Fig. 2. Cumulative non-compliance failures in UK in 2019−2020 (DWI, 2019, 2020).

2.2. Compliance failures

As shown in Table 1, 161 taste and odour (including four complaints from consumers for illness), ten turbidity, 40 lead, 14 nickel, seven aluminum, 65 iron, nine manganese, two nitrate and one copper failures were reported. In addition, 69 failures for fluoride, one failure for pesticide (oxadixyl), three failures for benzo(a)pyrene, and one failure for pH were reported (DWI, 2019). In 2020, 62 cases were reported regarding coliform bacteria, seven for turbidity failures and 37 for taste and odour failures, and 329 compliance breaches were recorded for fluoride concentration requirements (DWI, 2020). Fig. 3 shows the total number of physical, bacteriological and chemical compliance failures reported during 2019−2020. Consequently, these contaminants were selected to study their health impacts.

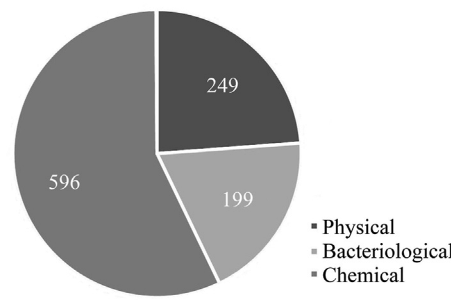

Fig. 3. Physical, bacteriological and chemical compliance failures in England and Wales during 2019−2020.

2.3. Secondary data collection

Secondary data collection was conducted to evaluate the health impacts of the selected contaminants (objective (1)) and to review the effectiveness of water quality monitoring (objective (2)). This was carried out through a systematic analysis of relevant literature retrieved from scholarly databases. The keywords and phrases of choices used were “contaminants in drinking water”, “monitoring drinking water quality” and “health impacts of contaminants in water”. Although significant literature is available, the geographical scope of the data was primarily limited to the UK, USA and Canada.

To reveal the most up-to-date scenario, secondary data collection was limited to the literature from the last six years with a few exemptions to aid the discussion. Altogether, 59 research articles were reviewed with relevant subject knowledge supported by the books *Basic Water Treatment* by Binnie et al. (2018), *Water Technology* by Gray (1999), *Principles of Water Treatment* by Howe et al. (2012) and *Introduction to Drinking Water Quality Testing* by the Centre for Affordable Water and Sanitation Technology (CAWST) in Canada (CAWST, 2009).

Table 1
Individual compliance failures of different drinking water quality parameters reported during 2019−2020.

Compliance parameter	Number of failures in 2019			Number of failures in 2020		
	Quarter 1	Quarter 2	Quarter 3	Quarter 1	Quarter 2	Quarter 3
pH	0	0	0	0	0	0
Taste	5	23	23	8	9	23
Odour	17	35	40	8	12	38
Turbidity	11	6	4	6	0	0
Coliform bacteria	11	6	50	13	28	40
Escherichia coli	0	1	8	0	0	3
Lead	16	17	22	8	0	22
Nickel	8	7	5	8	0	0
Iron	30	24	27	19	19	8
Copper	1	0	2	0	0	0
Pesticide	1	1	0	0	0	0
Benzo(α)pyrene	0	1	2	0	0	0

Note: Data were segregated into quarters. The omission of the quarter 4 results was either due to compliance reporting not taking place or the data being publicly unavailable. It may be also noted that zero can be interpreted as either no compliance failure or failures not reported or not checked.

The third objective of this review is to elaborate on the public perception of safe drinking water and compare it with WHO guidelines. Observations were contested with relevant guidance as presented in WHO (2017, 2018), the Department for Environment, Food and Rural Affairs (DEFRA), the UK (DEFRA, 2018), the Environment Agency (EA) in the UK, the United States Environmental Protection Agency (EPA) (EPA, 2017a, 2017b), the Centre for Disease Control and Prevention (CDC) in the USA (CDC, 2020b) and CAWST (CAWST, 2009). Lastly, the prescribed limits of each contaminant in different countries were compared, and the role of public water supplies in the UK, USA and Canada was discussed as a potential guideline for developing countries.

3. Characterising major contaminants in drinking water

The Safe Drinking Water Act (SDWA) defines a contaminant as any physical, chemical, biological or radiological substances or matter present in water at any concentrations. Contaminants are always present in water, and pure water does not exist in nature (Binnie et al., 2018). When it comes to characterising contaminants in drinking water, the primary categories are summarised in Fig. 1. The sources of some key contaminants found in drinking water are summarised in Table 2.

3.1. Physical contaminants

Due to the presence of suspended solids, physical contaminants affect the physical appearance of water. These may include sediment, dirt, clay or organic matter. They may impact colour, odour and turbidity (CAWST, 2009; EPA, 2017b; Binnie et al., 2018). Suspended solids (SS), such as dust, dirt, slit, clay and algae or any undissolved particles above 2 μm, are a primary category of physical contaminants. SS in water may give rise to colour and turbidity and can contain various pollutants and pathogens that are harmful to human health. Generally, SS can be easily removed by sedimentation or filtration (WHO, 2017; Binnie et al., 2018; CDC, 2020a).

3.2. Chemical contaminants

Chemical contaminants may be natural or synthetic elements and compounds that are inorganic or organic. Examples of such contaminants include arsenic, chlorine (or its derivatives), barium, boron, cadmium, manganese, molybdenum, selenium, sodium and uranium (CAWST, 2009). In addition, pesticides, pharmaceutical products, personal care products and dissolved organic matter also become part of chemical contaminants (CAWST, 2009; Binnie et al., 2018; Palansooriya et al., 2020). Inorganic contaminants include metals, heavy metals and salts. As water percolates through the beds of soil, it dissolves these elements (Howe et al., 2012).

3.3. Inorganic contaminants (IOC) with significant health risk

As listed in Table 1, one of the most significant inorganic contaminants found in drinking water is arsenic (As) that is naturally found in groundwater and sometimes in surface water in 30 countries including India, Nepal, Bangladesh, Iran, Indonesia, Vietnam, Brazil and Mexico. In South Asia alone, 65 to 100 million people are affected by consuming water containing high levels of arsenic. Intake of excess amounts of arsenic for prolonged periods may cause cancer in bladder, skin, kidney, liver and prostate (CAWST, 2009). WHO suggests that arsenic in drinking water should not exceed 0.05 mg/L (Hasan et al., 2019). If the arsenic level exceeds 10 mg/L, ion exchange or reverses osmosis is required for its removal. It can also be adsorbed using ferric hydroxide, activated alumina or bone char (Binnie et al., 2018). Heavy metals like As, cadmium (Cd) and

Table 2
Contaminants in drinking water and their sources.

Contaminant	Source	Reference
Suspended solids (dust, dirt, slit, clay and algae)	Soil erosion, water runoff and algal growth	CAWST (2009); EPA (2017b); Binnie et al. (2018)
Dissolved solids (below 2 μm)	Percolation of water through soil beds (natural) and anthropogenic activities	CAWST (2009); Binnie et al. (2018)
Heavy metals (Pb, Hg, As, Cu, Cr and Ni)	Industrial waste, erosion and corrosion	Chowdhury et al. (2016); Health Canada (2020)
Fluoride	Naturally found in both ground and surface water	WHO (2011, 2018); CDC (2020b)
Nitrite and nitrate	Nitrogen cycle, use of fertilizers, agriculture runoff and use of preservatives	Gray (1999); CAWST (2009); The Open University (2018)
Iron	Natural and corrosion in pipes	Chowdhury et al. (2016); WHO (2018)
Manganese	Naturally found along with iron in both surface and ground water	
Natural organic matter (NOM)	Decomposition of plants and animals	Jones and Bridgeman (2019); Health Canada (2020)
Polyaromatic hydrocarbons (PAHs)	Use of hydrocarbon-based fuels	Gray (1999)
Contaminants of emerging concern (CEC)	Cosmetics, pharmaceuticals and nano materials	Wilkinson et al. (2017); Yang et al. (2017); Kausley et al. (2019); Vashisht et al. (2020)
Microbial contaminants	Waterborne, atmosphere, human/animal faecal, sewers and wastewater seepage	CAWST (2009); Binnie et al. (2018); EPA (2018)
Disinfection bye-products (DBPs)	Chlorine or other biocides added may react with NOM in water to form DBPs	Binnie et al. (2018); ATSDR (2020); Health Canada (2020)

mercury (Hg) can bioaccumulate in the human body and may lead to cancer (Chowdhury et al., 2016).

3.3.1. Organic contaminants with established limits

These contaminants may emerge from industrial activity, agricultural lands (fertilizers and pesticides), livestock, overflowing sewers and defective waste treatment plants. They may include pharmaceuticals, body care products, polychlorinated biphenyls (PCB), benzene, toluene, xylene, polyvinyl chloride (PVC), styrene, volatile organic compounds (VOCs) and tetrachloroethylene (CAWST, 2009; Howe et al., 2012; CDC, 2020a). Natural organic matter (NOM) originates in water due to the biological degradation of plant and animal products (Jones and Bridgeman, 2019). NOM is the measure of total organic carbon (TOC) in water, which is mostly in solution form. The portion that can pass through a 0.45-μm filter membrane is called dissolved organic carbon (DOC). Organic matter plays an important role in the physical and chemical characteristics of water (Health Canada, 2020). It also affects the taste and colour of water and may cause the regrowth of pathogens (Jones and Bridgeman, 2019). Polyaromatic hydrocarbons (PAHs) are organic compounds containing more than one benzene ring.

3.3.2. Contaminants of emerging concern

Contaminants of emerging concern (CEC) are present naturally in the environment and also created by anthropogenic activities (Kausley et al., 2019). These contaminants may contain pharmaceuticals (as summarised in Table 3), body-care products and nano particles. Other CECs include surfactants and plasticizers, such as 4-nonylphenol (NP), 4-octylphenol (OP) and bisphenol A (BPA), in addition to perfluorinated substances, such as perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA). Some of these contaminants are recently been included by the European Union Council in the water directive to be monitored for their possible disastrous effects on human health (WHO, 2017; EPA, 2018).

3.4. Microbiological contaminants

Microbiological contaminants are the organisms present in water, called microbes (EPA, 2018). They include bacteria found in human and animal faeces that can contaminate water (Gray, 1999). Water-borne diseases caused by bacteria include diarrhoea, cholera and typhoid (CAWST, 2009). The presence of coliforms indicates that other harmful bacteria may also be present (EPA, 2017b). If coliform bacteria are found in water, *E. coli* test is performed to confirm whether the coliform is of faecal origin. The presence of any *E. coli* renders the water unfit for drinking purposes (Binnie et al., 2018). Other potential microbiological contaminants include viruses that are the smallest among pathogens. Water-transmitted viral pathogens that are classified to have a moderate to high health significance by WHO include adenovirus, astrovirus, hepatitis A and E viruses, rotavirus, norovirus and other caliciviruses, and enteroviruses including coxsackieviruses and polioviruses (Gall et al., 2015).

Table 3
Contaminants of emerging concern reported by Valbonesi et al. (2021).

Pharmaceutical	Use
Atenolol (ATE)	Anti-hypertensive
Caffeine (CFF)	Psychoactive
Carbamazepine (CBZ)	Anti-epileptic
Diclofenac (DCF)	Anti-inflammatory
Ibuprofen (IBU)	Anti-inflammatory
17-beta-estradiol (E2) and estrone (E1)	Natural estrogen
17-alfa-ethinylestradiol (EE2)	Synthetic estrogen

3.5. Radiological contaminants

Many natural and artificial radionuclides have been found in water, but most of the radioactivity is due to a relatively small number of nuclides and their decay products. Among these, the following emitters of radiation of low linear energy transfer (LET) are potassium-40, tritium, carbon-14 and rubidium-87. In addition, high-LET and alpha-emitting radionuclides, such as radium-226, polonium-210, uranium, thorium, radon-220 and radon-222, may also be present in varying amounts. Evaluating the radiation doses of radionuclides in water can be calculated following the methodology reported in the *National Committee of Radiation Protection (NCRP) Report 22* (National Committee on Radiation Protection, 1959).

4. Health impacts of contaminated drinking water

Contaminants in drinking water beyond allowable limits cause a range of health problems depending on the nature of the pollutants as summarised in Table 4. Ingestion of contaminated drinking water is responsible for 80% of the diseases in developing countries. As can be seen, contaminated drinking water is detrimental to the economy due to the lost work hours and incurred hospital expenses. It also affects the literacy rate as children are the highest affected group (Bradley et al., 2018). It is estimated that every one US dollar spent on the provision of safe drinking water enables the economy of the country to save five to 45 US dollars by reducing water-related diseases (Hunter et al., 2010).

5. Monitoring contaminants in drinking water

Fig. 4 summarises the different methods for monitoring the quality of drinking water. Water quality monitoring is a legal requirement both locally and internationally. It is a requirement by the Water Framework Directive (WFD) in the UK, the Clean Water Act in Canada and the Clean Water Act in the USA. Water quality monitoring involves regular data collection, strict observation and manual involvement using different methods as summarised in Table 5 (O'Grady et al., 2020).

Table 4
Human health effect of drinking water contaminants.

Contaminant	Potential health effects from long-term exposure above maximum contamination level	Reference
Arsenic (IOC)	A known carcinogen and may lead to lungs, bladder, kidney and prostate cancers Skin diseases, vascular diseases, neurological effects and birth defects Arsenic is ranked number one in the Agency for Toxic Substance and Disease Registry (ATSDR) substance priority list.	EPA (2017b); WHO (2017); Kausley et al. (2019); ATSDR (2020); CDC (2020b)
Aluminum (IOC)	No adverse health effects (EPA) Although the relationship between alzheimer and high aluminum level in drinking water cannot be totally negated, there is insufficient evidence for health-based guidance (WHO). Aesthetic effect that imparts colour to water (CDC)	EPA (2017b); WHO (2017); CDC (2020b)
Cadmium (IOC)	Cadmium is ranked number seven in the ATSDR substance priority list. Excess level of cadmium may damage kidneys.	CAWST (2009); EPA (2017b); Kausley et al. (2019); ATSDR (2020); CDC (2020b)
Chlorine as Cl_2 (D)	Irritation in eyes and nose and stomach problems (EPA) Normal chlorine dose has no adverse effect (CAWST). Aesthetic effect as it creates taste problems for the consumers (WHO)	CAWST (2009); EPA (2017b)
Chloride (IOC)	No health concern at levels normally found in drinking water (WHO) Studies reveal that high chlorides in water may affect kidney function (CAWST). Aesthetic effect and different taste (CDC)	CAWST (2009); WHO (2017); Kausley et al. (2019); CDC (2020b)
Fluoride (IOC)	A minimum fluoride level is necessary for good teeth. However, higher levels may cause staining and pitting in teeth and problems in joints and bones. Discolouration of teeth (CDC)	EPA (2017b); WHO (2017); Kausley et al. (2019); CDC (2020b)
Nitrate and nitrite (IOC)	May cause methemoglobinemia or blue baby syndrome (CAWST) Infants who consume high levels of nitrite or nitrate in drinking water for prolonged time may die if not treated (EPA).	CAWST (2009); EPA (2017b); CDC (2020b)
Iron (IOC)	Iron is not considered a direct health concern in water (WHO). Essential element for nutrition and no health-based guidance (CAWST) High levels may cause taste problems (Gray, 1999).	Gray (1999); CAWST (2009); WHO (2017); Kausley et al. (2019)
Manganese (IOC)	New evidence suggests that high concentrations of manganese in dissolved form results in learning impairment in children (WHO). Essential nutrient. However, both excess and deficiency can cause adverse impacts (CAWST).	CAWST (2009); WHO (2018)
Lead (IOC)	Adverse neurological effects, especially in children and pregnant women May cause kidney problems in adults May delay physical and mental development in children/infants (CDC) Lead is ranked number two in the ATSDR substance priority list.	CAWST (2009); EPA (2018); Kausley et al. (2019); ATSDR (2020); CDC (2020b)
Sulphate (IOC)	Excess sulphates of magnesium or sodium may cause a laxative effect. May cause salty taste in water (CDC)	Gray (1999); Wu et al. (2011); CDC (2020b)
Cyanide (IOC) as free cyanide	May cause nerve damage and thyroid problems Cyanide is ranked number 35 in the ATSDR substance priority list.	CAWST (2009); EPA (2018); ATSDR (2020); CDC (2020b)
Chromium (total) (IOC)	Allergic dermatitis (EPA and CDC) No toxicological data are available (CAWST). Chromium is ranked number 17 in ATSDR substance priority list.	CAWST (2009); EPA (2018); ATSDR (2020); CDC (2020b)
Copper (IOC)	It is both nutrient and contaminant. Can affect gastrointestinal tract (CAWST) Long-term exposure may cause kidney problems (EPA). May affect liver or kidney (CDC)	CAWST (2009); EPA (2018); CDC (2020b)
pH	No health-based guidance is proposed (CAWST). May affect the chemical treatment. The guideline value is 6.5−9.5 (WHO). Included in secondary drinking water regulation with a limit of 6.5−8.5 (EPA)	CAWST (2009); EPA (2018); WHO (2018)
Turbidity	High turbidity levels may be a health risk (CAWST). Turbidity is indicative of the efficiency of filtration to remove pathogens. High turbidity may be the source of bacteria and virus (EPA). Turbidity affects consumer acceptability and may hinder treatment processes. Higher turbidity levels may cause diseases due to pathogenic effects (CDC).	WHO (2017); EPA (2018); CDC (2020b)

(*continued on next page*)

Table 4 (*continued*)

Contaminant	Potential health effects from long-term exposure above maximum contamination level	Reference
Total dissolved solids (IOC and OC)	TDS may affect taste if their concentration is high (CAWST). TDS is included in the secondary drinking water regulation (EPA). High TDS may reduce palatability. However, no guideline is given (WHO). High TDS levels increase water hardness (CDC).	WHO (2017); EPA (2018); CDC (2020b)
Pesticide	Short-term risk is toxicity. Long-term effects may include cancer and reproductive risks (EPA). Pesticides used for vector control in drinking water lines should strictly follow local guidelines for the formulation (WHO). Exposure should be minimum for infants and pregnant mothers (CDC).	WHO (2017); EPA (2018); CDC (2020b)
Benzo(α)pyrene (OC and PAH)	May impair reproductive capabilities Risk of cancer (EPA and CDC) Presence in water is due to the lining of discontinued coal-tar pipes (WHO). It is ranked number eight in the ATSDR substance priority list.	WHO (2017); EPA (2018); CDC (2020b)
Carbon tetra chloride (OC)	May cause liver problems Increased risk of cancer (EPA and CDC) May affect liver and kidney Carcinogenic on animals, but the evidence for human not established (WHO)	WHO (2017); EPA (2018); CDC (2020b)
Benzene (OC)	Anaemia and may decrease platelets in blood Increased risk of cancer (EPA and CDC) Toxicity depends upon the product (WHO). Benzene is ranked number six in the ATSDR substance priority list.	WHO (2017); EPA (2018); CDC (2020b)
Dioxin (OC)	May impair reproductive capabilities Risk of cancer	WHO (2017); EPA (2018); CDC (2020b)
Vinyl chloride (OC)	Increased risk of cancer (EPA) Known carcinogen with certain PVC grades of pipes being the major source Level should be kept as low as possible (WHO). Vinyl chloride is ranked number four in the ATSDR substance priority list.	WHO (2017); EPA (2018); ATSDR (2020)
Faecal coliform and *E. coli* (M)	The presence indicates contamination with human or animal waste. May cause diarrheal diseases, nausea, cramps and headaches, especially in vulnerable people (EPA) Presence of faecal contamination. However, the absence of *E. coli* does not testify that the water does not contain other pathogens (WHO). Not a threat itself. It gives an indication about the possibility of pathogens (CDC).	WHO (2017); EPA (2018); CDC (2020b)

Note: IOC, OC, D and M stand for inorganic chemicals, organic chemicals, disinfectants and microorganisms, respectively.

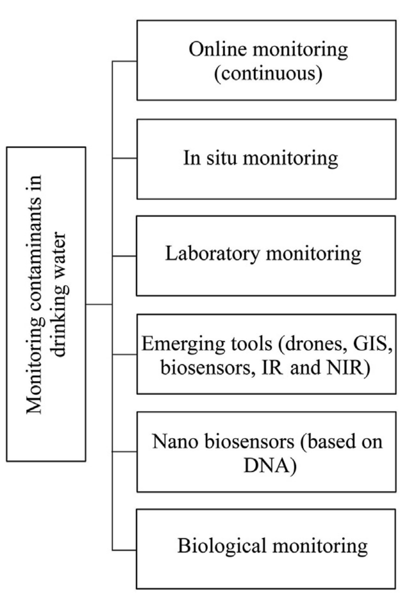

Fig. 4. Different methods for monitoring contaminants in drinking water.

6. Guide values and standards for safe drinking water

6.1. Definition of safe drinking water

Generally drinking water is considered safe if it does not pose any significant harms to humans (The Open University, 2018). However, according to WHO, safe water should also not contribute to any sensitivities that may occur during different stages of life (WHO, 2017). Perhaps the most useful definition is provided by CAWST (CAWST, 2009), where drinking water is considered safe if its physical, chemical and biological characteristics meet WHO guidelines or any other national standards. Some of these standards are of primary importance from a safety standpoint with limits as summarised in Table 6, while others are of aesthetic sense like taste and colour (Yan et al., 2016).

6.2. Difference between guidelines and standards

To ensure drinking water quality, WHO works with UN and periodically issues the *Guidelines for Drinking Water Quality*

Table 5
Comparison of established and emerging methods in water quality monitoring showing their respective advantages and limitations.

Instrument type	Monitored parameter	Advantage and limitation
Handheld meter	Total dissolved solids (TDS), electrical conductivity (EC), turbidity, pH and dissolved oxygen (DO)	Handheld meters are cost-effective, making them suitable for a wide range of laboratory scales and measurement scenarios. Although they are easy to use and operate, they are generally less precise in comparison to laboratory scale equipment. Continuous monitoring is not possible (CAWST, 2009; WHO, 2017; Binnie et al., 2018).
Spectrophotometer and inductively coupled plasma mass spectrometer (ICP-MS)	Majority of contaminants including metals can be detected.	A large number of contaminants can be measured. Results are fairly accurate and quick. Continuous monitoring is not possible (Heibati et al., 2017).
Online sensor	pH and EC	It offers the highest potential to detect abrupt change in water quality. It performs well in both static and dynamic conditions. National standards and WHO guidelines can only be met comprehensively through continuous online monitoring. These sensors cannot measure individual contaminants, which limits their usage (Banna et al., 2014; Eliades et al., 2015).
Emerging tools like capillary electrophoresis (CE), microfluidic sensors, biosensors and spectroscopic techniques including infra-red (IR) and near infra-red (NIR)	pH, EC, DO, organic contaminants and most of inorganic contaminants	These are the latest and emerging techniques that are fast, reliable and cost effective. They can be integrated into established monitoring systems with few false positives and negatives (Zulkifli et al., 2018). Their large-scale adoption and implementation are yet to be demonstrated. Their cost can be prohibitive to their adoption in developing countries.
Drone and geographic information system (GIS)	pH, TDS and conductivity	This is the latest technology that is emerging in the field of water quality monitoring. The techniques can also be experimented at limited scales, and they are currently expensive (O'Grady et al., 2020).
Nano biosensor	Inorganic metals, organic substances and CEC	Nano-biosensors are also emerging with their operation principles inspired by the principles of DNA. Almost all contaminants can be measured up to trace or below trace levels (Soukarié et al., 2020).
Biological monitoring	Monitoring of pathogens like coliform and *E. coli*.	One of the most significant parameters required to evaluate water quality in developing regions. Many water borne diseases may be controlled (WHO, 2017; Binnie et al., 2018; Blokker et al., 2018).

(GDWQ). The GDWQ suggests the official position of WHO on the safe limits of relevant chemicals in drinking water. These guidelines are prescribed by a team of experts and undergo rigorous scientific peer-review. Although it is not mandatory, a guideline is a limit prescribed by an institution that should not be exceeded, whereas a standard is a legal limit that needs to be followed to ensure safe drinking water (CAWST, 2009). For those chemicals identified with a threshold limit, the tolerable daily intake (I_{TDI}) is defined as the amount of a substance (expressed in milligrammes or microgrammes per kilogramme of body weight) that can be consumed through food and water for a lifetime without any adverse effects (with a safety margin). These guideline values (V_{g}) can be calculated using Eq. (1) (WHO, 2017):

$$V_{\mathrm{g}}=\frac{I_{\mathrm{TDI}}W_{\mathrm{b}}P}{C} \tag{1}$$

where W_{b} is the body weight, P is the faction of I_{TDI} that is allocated for drinking water, and C is the daily water consumption. I_{TDI} can be calculated with either (1) no observed adverse effect limit, (2) the lowest observed effect limit, (3) the lower confidence limit of the benchmark dose limit divided by the uncertainty factor or (4) the chemical-specific adjustment factor.

7. Discussion

7.1. Significance of contaminants reported in public water supplies

It can be seen from Table 1 that although continuous monitoring of numerous water quality breaches has been reported in the UK all year around, it is not of significant health concern. The health impacts of contaminants in drinking water, as summarised in Table 2, vary, whereas the recommended allowances (WHO, 2011, 2017, 2018) informed by relevant regulatory agencies differ between countries. Although most contaminants are detrimental to health, some elements like selenium, zinc, copper, chromium and fluoride can offer health benefits in limited quantities. Looking at the existing practices, the findings of DWI on the compliance of public water supplies to UK standards revealed 1 044 failures for the year 2019−2020, of which 34.19% were found to be health-related in areas as shown in Fig. 5(a). The remaining 65.81% of failures were only aesthetic as demonstrated in

Table 6
Limits for key contaminants in drinking water informed by a range of guidelines and standards from different countries (Kapp, 2005; Pakistan Environmental Protection Agency, 2008; BIS, 2012; Daud et al., 2017; WHO, 2017; Government of UK, 2018; Health Canada, 2020).

Contaminant	WHO	UK	USA	Canada	India	Pakistan
Arsenic	0.01 mg/L	0.01 mg/L	0 mg/L	0.010 mg/L (ALARA)	0.01 mg/L (A); 0.05 mg/L (P)	≤ 0.05 mg/L
Aluminum	0.9 mg/L	0.2 mg/L	0.05−0.20 mg/L	n/a but observed at 0.1−0.2 mg/L	0.03 mg/L (A); 0.2 mg/L (P)	≤ 0.2 mg/L
Cadmium	0.003 mg/L	0.005 mg/L	0.005 mg/L	0.007 mg/L	0.003 mg/L	0.01 mg/L
Chlorine as Cl_2	5 mg/L		4 mg/L	n/a but observed at 0.04−2.00 mg/L	0.2 mg/L (A); 1.0 mg/L (P)	0.2−0.5 mg/L(CT); 0.5−1.5 mg/L (S)
Chloride	NHC	250 mg/L	250 mg/L	n/a	250 mg/L (A); 1 000 mg/L (P)	250 mg/L
Fluoride	1.5 mg/L	1.5 mg/L	4 mg/L	1.5 mg/L	1 mg/L (A); 1.5 mg/L (P)	1.5 mg/L
Nitrate as NO_3	50 mg/L	50 mg/L	10 mg/L	45 mg/L	45 mg/L	≤ 50 mg/L
Nitrite as NO_2	0.3 mg/L	0.5 mg/L (CT); 0.1 mg/L (TW)	1.0 mg/L	3.0 mg/L		≤ 3 mg/L
Iron	NHC	0.2 mg/L	0.3 mg/L	n/a	1.0 mg/L (A); 1.5 mg/L (P)	1.5 mg/L
Manganese	NHC	0.05 mg/L	0.05 mg/L	0.12 mg/L	0.1 mg/L (A); 0.3 mg/L (P)	≤ 0.5 mg/L
Lead	0.01 mg/L	0.01 mg/L	0 mg/L	0.005 mg/L (ALARA)	0.01 mg/L	≤ 0.05 mg/L
Sulphate	NHC	250 mg/L	250 mg/L	n/a	200 mg/L (A); 400 mg/L (P)	n/a
Cyanide	0.05 mg/L	0.05 mg/L	0.2 mg/L	0.2 mg/L	0.05 mg/L	≤ 0.05 mg/L
Chromium (total)	0.05 mg/L	0.05 mg/L	0.1 mg/L	0.05 mg/L	0.05 mg/L	≤ 0.05 mg/L
Copper	2.0 mg/L	2.0 mg/L	1.3 mg/L	2.0 mg/L	0.05 mg/L (A); 1.50 mg/L (P)	2 mg/L
pH	NHC	6.5−9.5	6.5−8.5	n/a but observed at 7.0−10.5	6.5−8.5	6.5−8.5
Turbidity	0.2−0.5 NTU	4.0 NTU (CT); 1.0 NTU (TW)	n/a	0.1−1.0 NTU	1 NTU (A); 5 NTU (P)	5 NTU
Total dissolved solids	NHC	Conductivity of 2 500 μs/cm	500 mg/L	n/a but observed < 600 mg/L	500 mg/L (A); 2 000 mg/L (P)	≤ 1 000 mg/L
Pesticide	1.1 mg/L (each); 0.003 mg/L (total)	0.000 5 mg/L (total)			Various	
Benzo(α)pyrene (PAH)	0.000 7 mg/L	0.000 010 mg/L	0 mg/L	0.000 04 mg/L	0.000 1 mg/L (PAH)	0.01 mg/L
Carbon tetra chloride	0.004 mg/L		0 mg/L	0.002 mg/L		
Benzene	0.01 mg/L	0.001 mg/L	0 mg/L	0.005 mg/L		
Dioxin	0.05		0			
Vinyl chloride	0.000 3 mg/L	0.000 5 mg/L	0	0.002 mg/L (ALARA)		
Faecal coliform and *E. coli*		0 mg per 100 mL	0	0 mg per 100 mL in water sample	0 mg per 100 mL in water sample	0 mg per 100 mL in water sample

Note: "NHC" stands for "not of health concern", "NTU" denotes nephelometric turbidity units, "CT" represents consumer's taps, "TW" stands for treatment works, "ALARA" denotes "as low as reasonably achievable", "A" represents the acceptable limit, "P" denotes the permissible limit, "S" represents "at the source", and "n/a" denotes "not applicable".

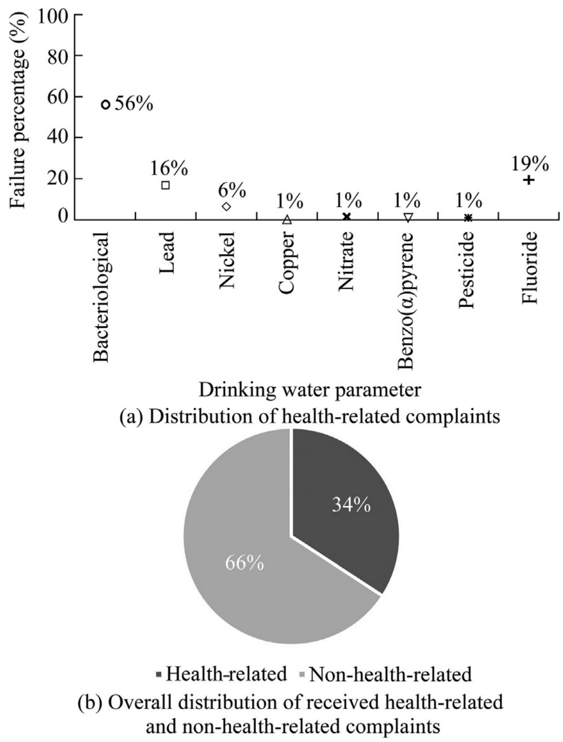

Fig. 5. Proportion of health-related compliance failures in supplied UK public water during 2019−2020.

Fig. 5(b), which is not of significant health concern. The high level of the reported bacteriological contamination can be due to the type of monitoring that was employed.

7.2. Contrasting water quality standards from key regions

While the discussion so far has been targeted toward identifying the primary contaminants of concerns in drinking water, the next objective is to regard water quality parameters and their monitoring. Although established instruments for water quality monitoring are currently effectively employed as summarised in Table 5, the advancements in the inductively coupled plasma mass spectrometer (ICP-MS) allow quick and easy testing for contaminants. Table 6 compares the water quality standards for different physical, chemical and biological contaminants in both developed countries and developing regions. Contamination of lead is of particular concern in developing regions as it infiltrates through plumbing systems and poses a significant risk (Fisher et al., 2021). This is of serious concern as there is no known safe level of exposure to lead as suggested by Needleman et al. (1979). Comparing the acceptable limits of lead according to different drinking water standards, the US prescribes the lowest allowable limit at 0 mg/L, followed by Canada at 0.005 mg/L. The UK and India seem to follow WHO recommendations at 0.01 mg/L. Contrastingly, Pakistan prescribes an allowable limit of 0.05 mg/L that is 400% higher than WHO recommendations.

Fig. 5 shows that lead contamination is also a problem in high-income countries, with the UK receiving around 16% of complaints in 2019−2020. This is primarily due to lead seepage to water from private wells and small piped systems. Although the situation in low- and middle-income countries has been less well studied, the problem is widespread. The exceedance of benzene(α)pyrene (carcinogen) was attributed to the degradation of coal tar lines that required replacing. The third quarter (July to September) of 2019 reported 75 cases of taste and odour complaints. The consumers also linked the taste of the supplied water to four self-assumed illnesses. This reveals that although taste and odour are not part of the critical compliance list, they should be monitored carefully by the PWS.

7.3. Standards versus literature from developing countries

The overall water quality standards in developing countries like Pakistan and India are similar to those in developed countries (Table 6). However, when it comes to fluoride as shown in Fig. 6, the allowable limit in the USA is higher than WHO recommendations. Nevertheless, when it comes to developing countries, there is a lack of monitoring and compliance that leads to insufficient water quality. Shahid et al. (2015) showed that the drinking water in some areas of Punjab Province (Pakistan) contained substantially high amounts of arsenic (32.2 μg/L) in water. The presence of coliform bacteria was also reported in a few cases. High arsenic in the capital city, Islamabad, Pakistan was also reported by Abeer et al. (2020), which is consistent with the *National Standards for Drinking Water Quality* (Pakistan Environmental Protection Agency, 2008).

8. Conclusions and recommendations

This paper reviewed the literature regarding selected contaminants in drinking water and their impacts on human health. This was followed by an evaluation of the current and upcoming practices in water quality monitoring and a comparison of the standards in five different countries, namely, the USA, UK, Canada, Pakistan and India. The review resulted in the following key observations and recommendations.

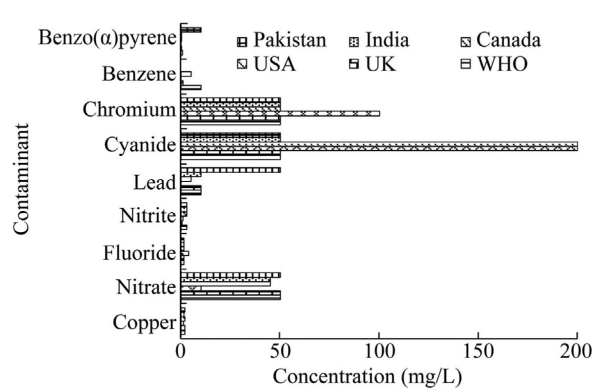

Fig. 6. Comparison of permissible limits of certain contaminants prescribed by WHO and different countries.

(1) The findings of DWI UK revealed 1 044 failures for the years 2019−2020, of which 34.19% were found to be health-related. 56% of these complaints were related to bacteriological contamination, followed by fluoride (19%), lead (16%) and nickel (6%). Other contaminations were due to copper, nitrate, benzo(α)pyrene and pesticides that were limited to 1% of the overall health-related complaints. The remaining 65.81% of failures were only aesthetic, which was not of significant health concern. The high level of the reported bacteriological contamination can be due to the type of monitoring that was employed.

(2) A continuous online monitoring system is vital to the maintenance of the water parameters in control limits and sustentation of the needs of the Water Framework Directive. Plumbosolvency control in water distribution networks is vital to the protection of consumers from the risk of lead poisoning. This can be achieved by controlled orthophosphate dosing. However, the impact of phosphate dosing on bacterial growth needs to be monitored.

(3) Elevated metal concentrations in semi-urban water supply systems were found in the USA. Certain regions showed the highest levels of uranium, selenium, barium, chromium and arsenic concentrations. Even at low concentrations, uranium represents an important risk factor for the development of chronic diseases.

(4) In most cases, public water supplies provide safe drinking water. However, occasional irregularities in controlling water parameters have been recorded and made publicly available by the regulatory authorities. The majority of these shortfalls are attributed to failures in the calibration of meters, maintenance of equipment and staff training.

(5) Although the majority of water quality standards in developing countries are consistent with WHO recommendations, the actual values from the literature showed high incidents of arsenic contamination. As such, it is recommended that effective and continuous water quality monitoring should be implemented.

(6) Comparing the standards between different countries, the allowable limit for fluoride in the USA was found to be significantly higher than WHO recommendations.

(7) Lead contamination is of particular concern in developing regions as it infiltrates through plumbing systems and poses a significant risk. Comparing the acceptable limits of lead according to different standards, the USA prescribes the lowest allowable limit at 0 mg/L, followed by Canada at 0.005 mg/L. The UK and India follow WHO recommendations at 0.01 mg/L. Contrastingly, Pakistan prescribes an allowable limit of 0.05 mg/L that is 400% higher than WHO recommendations.

(8) The exceedance of benzene(α)pyrene (carcinogen) in the UK public water supplies was attributed to the degradation of coal tar lines that required replacing.

(9) Excessive use of chemical treatment, such as chlorine, needs to be avoided. Chlorine and its associated products allow pathogens to develop immunity to protect themselves. Furthermore, possibly keeping the source clean by taking steps to minimise water pollution can offer a sustainable solution for the long term.

(10) Public awareness needs to be raised about the perception of water quality and safety. This is for the developing regions and developed countries as well.

Declaration of competing interest

The authors declare no conflicts of interest.

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