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Recent trends of microbial decontamination for occupational, industrial and domestic applications

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Abstract

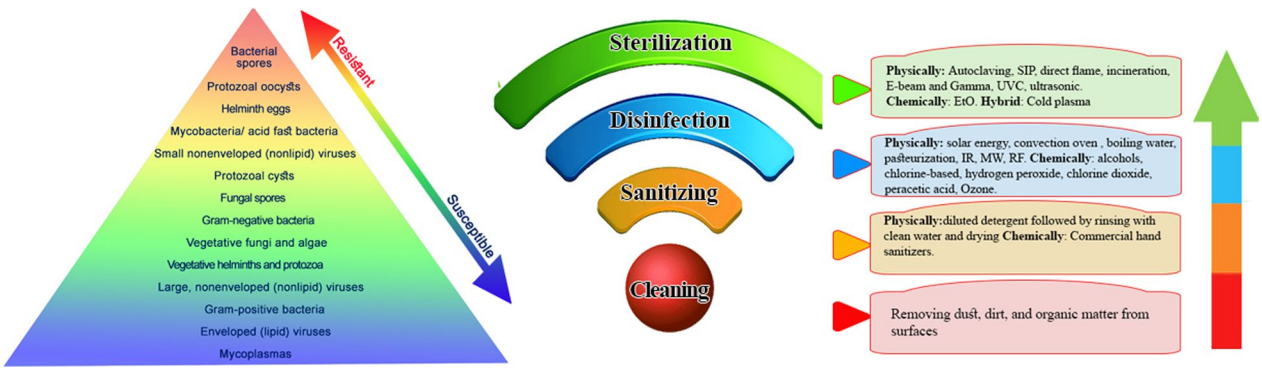
Background: Nowadays, engineers face challenges in developing novel technologies to find environmental and industrial solutions to address microbial contamination Microbes and treated objects differ significantly in their ability to tolerate the decontamination methods.

Main text: This work introduces a comprehensive review of recent trends of microbial decontamination for occupational, industrial, and domestic applications to help design and optimize suitable decontamination approaches.

Conclusions: Decontamination methods vary in their effectiveness towards microorganisms as sanitizing is the least effective decontamination method; disinfectants and antiseptics provide a higher level of decontamination. However, the best decontamination method is sterilizing. Hence, Microbial decontamination methods must be designed according to the level of microbes resistivity and the sensibility of the treated material.

Keywords: Disinfection, Microbial decontamination, Microbial resistance, Sanitizing, Sterilization

Graphical abstract



Background

The increased attention on the air, water, and food safety, and the precedence of pathogens that cause significant disease outbreaks, has become the primary concern of governments, international agencies, and researchers worldwide. These challenges have increased global

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demand for efficient decontamination methods to address microbial contamination.

Decontamination methods can be classified according to microbial decontamination level into cleaning, sanitizing, disinfection and sterilization. They can also be classified into physical and chemical decontamination methods according to the decontamination process. However, no single decontamination method suits all objectives, and each method has its benefits and drawbacks, and research continues to assess those methods that are most practical for each purpose. Research suggests that some objectives require combining two or more methods. Selecting the suitable method depends on some factors, including the variance of microorganisms' ability to tolerate destruction by physical or chemical means, the nature of the decontaminated substrate, and the method's safety.

Hence, engineers nowadays face challenges in developing novel technologies to find environmental and industrial solutions to address microbial contamination, maintain public health, and prevent the prevalence of pathogens and pandemics. These challenges force engineers to be updated about recent trends of microbial decontamination to help them design and optimize suitable decontamination methods (Alice et al. 2005; Freeman et al. 2014; Pichel et al. 2019; Waldrop 2015).

This review shed light on the state-of-the-art physical and chemical microbial decontamination technologies, including sanitizing, antiseptic, and sterilization, regarding their effectiveness against microbial resistance.

The concept of microbial decontamination and resistance of microorganisms

Decontamination is when pathogens are removed, inactivated, or destroyed (Veerabadran and Parkinson 2010). A pathogen is a microbe that causes disease. The term microbe encompasses all microorganisms, living entities, such as bacteria, fungi, mold, yeast, algae, and non-living entities, such as viruses. In other words, decontamination is the technique or process of removing, inactivating, or killing pathogens to make an environment clean and safe (Fraise et al. 2008; Godbey 2014; McDonnell 2017).

Microorganisms differ significantly in their ability to tolerate destruction by physical or chemical means. As demonstrated in Fig. 1, vegetative bacteria, viruses, fungi, and mycobacteria are often considered the least resistant to decontamination and can usually be reduced to a sanitary level by sanitizers or destroyed by disinfection methods. These different types of microorganisms are listed below in order of the high resistance to less resistance.

- *Bacterial endospores, oocysts, and eggs* Bacterial endospores and other protective shell structures such as oocysts and eggs are the most resistant type of pathogen and are only killed by sterilization processes, which can be physically or chemically, and can destroy the robust protective layers of these endospores and shell structures, destroying their genomes (Lai et al. 2003; Riesenman and Nicholson 2000; Setlow 2006; Swenson 2012). It is noteworthy that endospores are the most resistant type of pathogen, and they require extreme sterilization methods to destroy them. Endospores are a pathogen's method of surviving in extreme conditions. For example, *Bacillus* species endospores can resist and survive extreme conditions, such as highly acidic environments, prolonged exposure to high temperatures, non-ionizing, and ionizing radiation, and strong antibiotics ampicillin cephalothin and oxacillin (Berg and Grecz 1970; Byrne et al. 2006; Clavel et al. 2004; Schlegelova et al. 2003; Setlow 1995). These endospores have multiple protective layers, which act as barriers, and accounts for their extreme resistance to decontamination. The first barrier is the external layer, consisting of either an exosporium or spore coat. The exosporium comprises several different proteins, while a spore coat consists of proteins and glycoproteins. The external layer can filter and detoxify many environmental contaminants (Lai et al. 2003; Setlow 2006). This external layer is followed by a beneath layer known as the cortex, forming a thick layer of peptidoglycans. The cortex protects the core from destruction by organic solvents. The third barrier, situated beneath the cortex, is the cell wall, composed of peptidoglycans. Beneath the cell wall is a cell membrane, which safeguards the central core, and the final barrier is the central core, which consists of

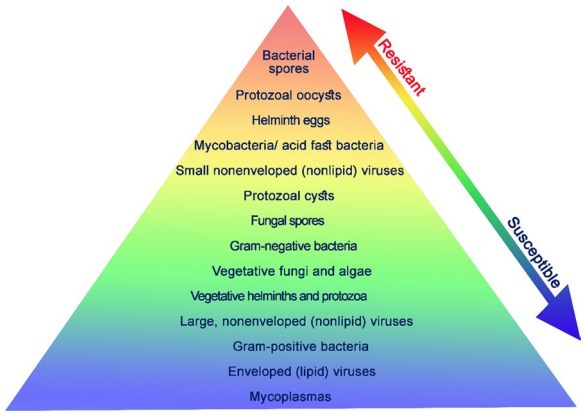

Fig. 1 The resistance of the microorganisms toward decontamination methods (drawn based on data given from (Traverse and Aceto 2015)

small acid-soluble binding proteins (SASP) that protect the DNA. Therefore, spores can survive for many years until favorable conditions arise, at which point they can then develop into vegetative cells (Driks 2002; Riesenman and Nicholson 2000; Setlow 2006).

- *Protozoa* Protozoa are microscopic unicellular organisms widespread in almost every habitat. Some species of protozoa are commensal and are not pathogenic to their hosts, whereas others are pathogenic and may cause a range of diseases from mild in severity to life-threatening, such as malaria. Infection from protozoa can be caused by contaminated water, food, and soil via sporulated oocysts passed in the host's feces. Protozoal oocysts, which are an important stage of the life cycle of protozoa (CDC 2004; Yaeger 1996), have a high level of resistance to chemical and physical decontamination treatments due to their protective membrane or hardy cell wall that is composed of two layers of over 90% protein. The outer layer of the oocyst wall contains mainly lipids-free quinone-tanned proteins, while the inner layer consists of a lipid-protein matrix (Mai et al. 2009).
- *Helminth* Another severe pathogen is helminth that causes parasitic infections that lead to the tropical disease, Helminthiasis. The female helminth worm deposits the eggs into the host in a process known as oviposition. The helminth eggs are highly resistant to chemical and physical decontaminations because their three-layered structure consists of proteinic, chitinous, and lipoidal layers, which provides resistance to several conditions and is considered the primary constraint for reusing water and wastewater (Jimenez 2007; WHO 2006b).
- *Fungi* Fungi and fungal spores also exhibit high resistance to decontamination treatments (Ma and Bibby 2017). Waterborne fungi are considered responsible for environmental problems such as turbidity, odor, and mycotoxin emissions, in addition to waterborne diseases caused by *Aspergillus spp*. and *Penicillium* spp. (Curtis et al. 2009; Hageskal et al. 2006; Oliveira et al. 2020; Pereira et al. 2009).
- *Bacteria* Bacteria have different resistivity against the decontamination methods according to their cell wall structure. Bacteria can be classified into Gram-Positive (GP) and Gram-Negative (GN) based on the cell wall structure. The cell wall of GP bacteria is characterized by a thick peptidoglycan layer with no outer lipid membrane, while the peptidoglycan layer is thin in GN bacteria and supported with an outer lipid membrane (Gram 1884). Notably, 90–95% of GN bacteria are pathogenic and are often implicated in severe diseases, such as Cholera caused by *Vibrio cholerae*, while most GP bacteria are nonpathogenic (Abe et al. 2010; Alexandraki and Palacio 2010). Although these pathogenic GN bacteria show more resistance to antibiotics than GP strains, they are more susceptible to decontamination methods and can be easily decontaminated. Comparatively, GP bacteria have more resistance to decontamination methods but tend to be less harmful to humans (Howie et al. 2008; Traverse and Aceto 2015).
- *Mycobacteria* Another microorganism, mycobacterium, has its name from the Latin word *myco*, which refers to fungus because they grow in a mold-like manner. Mycobacteria are responsible for severe diseases in humans, such as tuberculosis and leprosy (Ryan and Ray 2004). Mycobacteria show a high level of resistance to chemical and physical decontamination methods due to their cell wall, which is composed of hydrophobic mycolic acid and peptidoglycan layers that are interconnected by a highly branched polysaccharide (arabinogalactan), which represents about 80% of the cell wall (Alderwick et al. 2015; Jackson 2014).
- *Virus* The extracellular form of a virus that spreads from one organism to another is called a virion. In contrast to other microorganisms, viruses can not be considered living organisms as they lack a metabolism system. A virion consists of a viral genome (containing both DNA and RNA) enclosed in a protein capsid that protects the genome. According to their cell membrane, viruses can be classified into two types; enveloped and non-enveloped. Viruses are referred to as enveloped when the protein capsid is surrounded by a membrane ("envelope"), which is composed of a lipid bilayer studded with virus-coded proteins in the shape of spikes or knobs, called peplomers. The role of the biological membrane is to protect the virus against attack from the host immune system. Viruses without a membrane are known as non-enveloped or "naked" viruses. Contrary to what one would expect, non-enveloped viruses are the most resistant to decontamination methods, and smaller non-enveloped viruses are more resistant than larger ones. This is because outer lipid bilayer "envelopes" can be quickly neutralized by various chemical and physical agents, and a virion is only infectious if it is fully intact. Hence, if the envelope is destroyed, a virion is no longer infectious (Gelderblom 1996; Howie et al. 2008; Traverse and Aceto 2015).

Types of microbial decontamination

According to the Environmental Protection Agency (EPA), there are three categories of microbial treatments based on the level of effectiveness of decontamination; sanitizers, disinfectants, and sterilants (EPA). Sanitizing is considered the least effective decontamination method,

as sanitizers clean surfaces of pathogens to be safe from a public health perspective but without ultimately killing microbial populations. Sanitizers can be applied on inanimate (non-living) surfaces and live tissues (e.g., skin). Sanitizers that can be applied on skins are known as antiseptics (Mahmood et al. 2020).

Disinfectants provide a higher level of decontamination than sanitizers. It is worthy of mentioning that the EPA includes strong antiseptics within disinfectants. Although both disinfectants and antiseptics may contain the same microbial pesticide, the difference is that disinfectants are used for inanimate surfaces, while antiseptics are applied to live tissue. On the other hand, sterilizing is considered the best decontamination method, killing vegetative microorganisms and their spores.

Sanitizing

Sanitizing is the least decontamination method in which microbial population is considered safe to public health. Sanitizing can be achieved either by removing the microorganisms from the treated surface without inactivation or reducing, but not necessarily eliminating microorganisms to a level that can be considered nonpathogenic. The word "Sanitizing" is defined in the Cambridge dictionary as making something spotless (CAMBRIDGE 2016), which means safe to use or consume without causing diseases from the public health standpoint. Sanitizers may have a two-stage approach; clean and disinfect. However, the disinfection efficiency in sanitizers is limited compared with disinfectants, and it depends mainly on the contact time and the biocide concentration in the sanitizer.

While sanitizing is considered the lowest level of decontamination, cleaning, an essential component of the process, can be considered a pre-elementary level. Cleaning removes dust, dirt, and organic matter from surfaces but does not remove microorganisms. However, cleaning is essential to remove any materials that interfere with the sanitizer's effectiveness. It is worth mentioning that some sanitizers and disinfectants have one-step action, which means they can clean and sanitize or disinfect in the same process (Rutala and Weber 2014). Sanitizing can be achieved by using diluted detergent.

An everyday example is the process of washing hands, clothes, utensils, and cutlery manually or in washing machines. In this process, removing microbes is achieved by applying diluted detergent followed by rinsing with clean water and drying. Ultrasonic can boost sanitizing of inanimate objects by creating bubbles in a liquid that help penetrate detergent into objects (Veerabadran and Parkinson 2010).

Commercial hand sanitizers play an influential role in preventing contagious pathogens by eliminating bacterial and viral pathogens. The nomenclature of hand sanitizer is a bit of a misnomer, and the proper name should be hand antiseptic. This correct name is because the main component of the hand sanitizer is alcohol, which is considered a higher level of decontamination than washing hands with soap and water (i.e., diluted detergent). Nevertheless, "Centers for Disease Control and Prevention" (CDC) suggests washing hands with soap and water over using hand antiseptic (Gerberding et al. 2002). This suggestion agrees with the "Canadian Medical Association" (CMA), which pointed out that hand antiseptic may not be an adequate substitute for soap and water (Vogel 2011).

Disinfection

Disinfection is a process of destroying all vegetative pathogens. However, the more resistant endospore might not be killed (Wilson and Nayak 2019). Physical and chemical methods are applied to disinfect liquids, gases, and solids.

Physical methods of disinfection

Physical methods of disinfection include heat, including solar, dry, and moist heat, in addition to non-ionized radiation such as infrared, microwaves, and longer ultraviolet waves.

Solar energy Solar energy is one of the old, widely used, low-cost decontamination methods. The disinfection is accomplished by prolonged exposure of the desired object under sunlight, allowing both UV transmission and temperature increases, leading to the inactivation of the pathogen (Wegelin et al. 1994). The increase in temperatures without UV radiation is insufficient for disinfection (Martín-Domínguez et al. 2005). It is noteworthy that the direct surface contact with solar radiation help achieves a satisfying degree of disinfection at a lower temperature. In a study for the effect of solar energy, *V. cholerae* and *E. coli* were inactivated at 40 °C when subjected to the solar radiation (Berney et al. 2006; McGuigan et al. 1998) provided that no barriers to the solar energy such as dirt and turbidity (Keogh et al. 2015; Martín-Domínguez et al. 2005).

The benefits of solar decontamination include its simplicity and low cost, independence of electricity, absence of need or formation of chemical or harmful byproducts, potential effectiveness against bacterial, viruses, and protozoa. However, solar decontamination has some limitations and drawbacks, including its dependence on climate conditions, the need for pretreatment for turbid samples, and the relativity long treatment time (Pichel et al. 2019).

Dry heat Dry heat disinfection can be conducted by hot air, and it is considered a more convenient method of con-

tamination for objects that cannot be disinfected by steam due to the damaging effects or failure of steam penetrating (Darmady et al. 1958). Hot air disinfection is mainly used for disinfecting heat-resistant inanimate objects such as glass and metal by using a forced convection oven at a temperature of 160 °C for 2 h or 170 °C for 1 h (Joslyn 2001). Dry heat destruct pathogens by depyrogenation of the bacterial cell (Ludwig and Avis 1990). Nevertheless, although dry is beneficial in terms of nontoxicity, availability, spores of some bacteria are resistant to dry heat (Sandle 2013a), besides it has a limitation for some materials such as plastic and rubber items and the cost of electricity (AORN 1992).

Moist heat The most common techniques of moist heat are boiling water and pasteurization. Boiling water is widely used globally for disinfection. The required time depends on water temperature. Six seconds are required when water boils at 100 °C, 60 s are required when water's temperature is 90 °C, and 600 s are required when water's temperature is 80 °C (McDonnell 2017). Despite the advantages that boiling water offers to disinfect objects in terms of availability, efficiency, and cost feasibility. Some drawbacks should be considered when using boiling water for disinfection, as some pathogens are only inactivated, which means the cells can survive at viable but nonculturable (Liu et al. 2020). Moreover, repeated heat exposure may reduce some objects' function over time, especially those are made of plastic components (Collins et al. 2019).

Pasteurization is another way of disinfection by moist heat, which is used widely in the dairy and food processing industries for food preservation purposes. The advantage of pasteurization systems is that they can be scaled down to meet small quantities with a corresponding decrease in cost (Andreatta 2007). In pasteurization, the liquid is heated without boiling. Pasteurization aims to eliminate pathogens to ensure fluid safety to prolong its shelf life (Keskin and Gulsunoglu 2012). Since pasteurization does not kill all pathogens, liquid might need a quick cooling after the heating to restrict the growth of microorganisms. The reduction of the pathogen population depends on the temperature, process time, and pathogen resistance (Islam and Johnston 2006). It is worth mentioning that each type of dairy or food product requires a different pasteurization method. There are five standard methods of industrial pasteurization(Al-Attabi et al. 2009; ChemViews 2012; Ciochetti and Metcalf 1984; Deeth and Datta 2011; Wright 2019): (1) Vat Pasteurization, also known as the "Holder of Pasteurization method" (HoP), is a batch operation in which temperature is held at (62.8–68.3 °C) for 30 min, and it is used to pasteurize milk, egg nog, and frozen dessert mixes, (2) High-Temperature Short time (HTST), which is a contentious operation in which temperature is held at (71.7 °C) for 15 s, and it is used to pasteurize milk, (3) High Heat Short time (HHST) is a contentious operation in which temperature is held at (88.3–100 °C) for (15–0.01 s), and it is used to pasteurize milk, (4) Ultra-High Temperature (UHT), which is a contentious aseptic operation in which temperature is held at (135–150 °C) for (2–15 s), and it is used to pasteurize milk and cream, and (5) In-container sterilization, which is a batch operation in which temperature is held at 116 °C for 20 min, and it is used to sterilize canned products.

It is noteworthy that high-temperature short-time methods (HTST, HHST, and UHT) are preferable to HoP. This preference is because High-temperature short-time methods preserve the antioxidant and antimicrobial properties of the products (Baro et al. 2011; Donalisio et al. 2018; Escuder-Vieco et al. 2018; Mayayo et al. 2015; Peila et al. 2017) in addition to its efficacy in the eradication of pathogens (Donalisio et al. 2018).

Non-ionizing radiations Non-ionizing radiations, including infrared, microwaves, radiofrequency, and longer ultraviolet, are used for disinfecting inanimate objects. They are characterized by their long wavelengths, low frequency, and low energy that lead to bending and vibrating of the bonds or lead to the excitation of electrons, which increases the temperature.

Infrared radiation (IR) in the range of 0.78–1000 μm, generates heat in the exposed materials by oscillating atoms and molecules.IR is subdivided into Near-infrared (NIR) (0.78–3 μm), Mid-Infrared (MIR) (3–50 μm), and Far-Infrared (FIR) (50–1000 μm). The penetration power of NIR is more significant than FIR; therefore, FIR is commonly used for heating purposes, while NIR is more implemented for disinfection. NIR can penetrate the tissues deeply without photoinduced cytotoxicity (Han et al. 2020; Zou et al. 2021). Hence, NIR effectively disinfects viruses, bacteria, and fungi on food products such as cereals, nuts, and fruits, while FIR disinfects surface decontaminants such as disinfecting shell eggs. For example, Wang et al. disinfected fungi *Aspergillus flavus* in freshly harvested and stored rice that elevated the rice temperatures to 60 °C for 120 min (Wang et al. 2014). Hamanaka et al. combined infrared for 30 s and ultraviolet irradiation for 60 s to extend the fruits' shelf life (Hamanaka et al. 2011). Bingol et al. treated almonds at 90 °C for 10–15 min by NIR radiation that significantly deactivated the *Pediococcus population* (Bingol et al. 2011). Alkaya et al. decontamination of *Salmonella Enteritidis* in shell eggs using FIR for 110 s without denaturation in albumen or yolk index (Alkaya et al. 2016).

Microwave (MW) and radiofrequency (RF) are electromagnetic radiation that can penetrate materials and

generate heat. MW and RG are used mainly to disinfect food materials as they can destruct microorganisms without a significant effect on the chemical composition of the food. MW and RF denaturate microorganisms' enzymes, proteins, and nucleic acids thermally, impairing their biochemical activities (Dev et al. 2012; Vijay et al. 2021).

Ultraviolet radiation is an electromagnetic wave in the range of (10–400 nm), and it is subdivided into several ranges. The most common ranges with practical importance are UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm) (Gray 2014). While UVA radiation is far less effective for microbial decontamination, but UVB and UVC demonstrate higher levels of microbial decontamination (Gómez-Couso et al. 2010). UVB demonstrates three orders of microbial decontamination magnitude than UVA (Setlow 1974). UVC has a potent sterilization effect on viruses and bacteria, and it will be discussed in detail in the sterilization section (Wang et al. 2009; Zhao et al. 2013). The most significant disinfection effect of UVB is at wavelengths between 300 and 310 nm, and it is mainly used to disinfect drinking water(Mbonimpa et al. 2012).

Disinfection by non-ionizing radiation has many benefits, including its effectiveness against various pathogens such as viruses, bacteria, and spores and the absence of need or formation of chemical or harmful byproducts. However, its limitations include its dependence on electricity and a relatively high operating cost. Radiation sources also need a periodic check for their effectiveness and a periodic replacement. Turbid samples need pretreatment to ensure adequate decontamination. It is noteworthy that some radiation sources, such as UV lamps, contain mercury, which is poisonous and needs a waste control and disposal system (Pichel et al. 2019).

Filtering membranes Filtering membranes are used to decontaminate the substrates by either interception or disinfection of airborne respiratory aerosols by adopting them in high-performance filters such as "High-Efficiency Particulate Air" (HEPA) filter that can capture both contaminants of (≥ 0.3 μm) and smaller viruses (≈ 0.1 μm) (Kowalski et al. 1998; Yamada et al. 2006).

In order to achieve the optimum control of indoor air, heating, ventilating, and air-conditioning (HVAC) systems should be designed to ensure both comfort and asepsis according to the "American Society of Heating, Refrigeration and Air Conditioning Engineers" (ANSI/ASHRAE/ASHE 2008). HVAC systems should be provided with particle filters to minimize the risk of airborne infectious disease transmission by installing filtration banks of minimum "Minimum Efficiency Reporting Values" MERV to capture and filter microorganisms (Azimi and Stephens 2013; Lynch and Goring 2020). MERV is an essential parameter in comparing the performance of different filters. It is used to rate the filters according to their ability to capture particles of sizes (0.3–10 μm). The MERV rating is on a scale of 1–20, and the higher the MERV rating, the better the filter is at trapping specific types of particles. MERV-13 can capture particles of size (0.3–1 μm) with 75% efficiency, and particles of size (1–3 μm) with 90% efficiency, thus it is capable of capturing lint, pollen, dust, pet dander, smoke, mold spore, backing flour and smog, in addition to airborne pathogens such as bacteria and viruses. Table 1 breakdowns the MERV rating of particle filter make, model, and uses. Another essential factor to be considered is "Air Changes per Hour" (ACH), which is calculated as the air volumetric flow rate in a confined area divided by the volume of the area. The minimum recommended value of total ACH is 4, which helps maintain the microbial level of the air within safe limits according to the "American Society of Heating Refrigeration and Air Conditioning Engineers"(ANSI/ASHRAE/ASHE 2008).

Microbial decontamination using filtration has many advantages, including its simplicity and the absence of need or formation of chemical or harmful byproducts. However, its limitations include that the required level of decontamination depends on the filter type and pore size, and it requires routine cleaning and maintenance. Moreover, their operating cost is high, specifically for membranes with smaller pore sizes (Pichel et al. 2019).

Chemical methods of disinfection

A broad range of chemicals such as acids, alkalis, alcohols, halogens, and halogen-releasing agents can be used as disinfectants. These chemicals are characterized by a broad antimicrobial spectrum, short kill-contact time, remaining wet long enough to meet listed kill-contact times, not affected by Interfering environmental subjects, nontoxic, nonflammable, chemically stable, soluble in water, economical, and easy to be applied (Molinari et al. 1987; Rutala and Weber 2014, 2016). They can be applied in liquid, mist (fog), or fume. Fumigation, in which liquid aldehyde and liquid permanganate are mixed to produce fumes, has been banned by numerous regulatory agencies due to the carcinogenic effect. However, liquid chemicals can be applied in the form of fog, which can be a "dry fog" when the fog particles size are (1–10 μm), or "wet fog" or "mist" when the particles size are (20–50 μm). The nomenclature of "dry fog" is because fog is seemingly dry, in addition to its fast dryness on surfaces. It is worth noting that applying disinfectants as the fog is preferable to apply it in liquid form, as the fine droplets with small weight and high surface area of fog particles increase the contact surface with the (Hayrapetyan et al.

Table 1 MERV rating of particles filters and make, model, and uses

MERV rating	Performance to capture particles of sizes				Example of filter make and model	Application and uses
	(3–10) µm	(1–3) µm	(0.3–1) µm	< 0.3 µm		
MERV-1	< 20%	N/A	N/A	N/A	MERV-1 filter (G1)	Capture large particles such as fibers, dust mites, and pollen
MERV 2	< 20%	N/A	N/A	N/A	True blue model 114201	
MERV 3	20–34%	N/A	N/A	N/A	Flanders NaturalAire	MERV-1 and 2 are used as pre-filter to capture most larger airborne particles after the air is blown into the machine, while MERV 3and 4 are suited for window air-conditioning units
MERV 4	35–49%	N/A	N/A	N/A	E–Z flow air filter model 10055.01162	
MERV 5	50–69%	N/A	N/A	N/A	3 M filtrete 100 MPR	Capture large particles such as lint, household dust, mite debris, and mold spores
					3 M filtrete 300 MPR	
MERV 6	70–85%	N/A	N/A	N/A	Flanders air filter, MERV 6	
MERV 7	≥ 85%	N/A	N/A	N/A	3 M filtrete 600 MPR	Provide very good for most residential, pet owners, rural, dusty areas, and industrial workspace
MERV 8	≥ 85%	N/A	N/A	N/A	Flanders Pre-pleat 40	
					Flanders NaturalAire Standard	
					Ace pleated model 4122354	
MERV 9	≥ 85%	< 50%	N/A	N/A	N/A	Capture lint, pollen, dust, pet dander, smoke, mold spore, baking flour and smog
MERV 10	≥ 90%	50–64%	N/A	N/A	Glasfloss industries ZLP16251 Z-Line Series	
MERV 11	≥ 90%	65–79%	N/A	N/A	3 M filtrete 1000 MPR	Provide excellent filtration for most residential, pet owners, rural, dusty areas and industrial workspace
					3 M filtrete 1085 MPR	
					Ace micropartivle model 4,122,354	
MERV 12	≥ 90%	80–89%	N/A	N/A	3 M Filtrete 1500 MPR	
					3 M filtrete 1550 MPR	
MERV 13	≥ 90%	≥ 90%	< 75%	N/A	3 M filtrete 1900 MPR	Capture lint, pollen, dust, pet dander, smoke, mold spore, backing flour and smog, in addition to airborne pathogens such as bacteria and viruses
					3 M Filtrete 2200 MPR	
					Aeolus synthetic mini-pleat	
					Aerostar pleated air filter	
MERV 14	≥ 90%	≥ 90%	75–84%		Filtrete 2800 MPR	Provide excellent filtration in smoking lounges, hospital inpatient care and general surgery, and superior commercial and electronic manufacturing
MERV 15	≥ 90%	≥ 90%	85–94%		Nordic pure	
MERV 16	≥ 90%	≥ 90%	≥ 95%		Lennox X7935	
MERV 17				> 99.97 on 0.30 µm particles	IEST Type A	Provide ultimate decontamination up to 6 log reduction for clean rooms, pharmaceutical manufacturing facilities, carcinogenic and radioactive materials
MERV 18				> 99.99 on 0.30 µm particles	IEST Type C	
MERV 19				> 99.999 on 0.30 µm particles	IEST Type D	
MERV 20				> 99.9999 on 0.10–0.20 µm particles	IEST Type F	

2020; Wood et al. 2013). Fogging machine generates high dense suspended aerosols in the air produces fog at room temperature using ultrasonic technology (Hayrapetyan et al. 2020; Hidy 1984; Richter et al. 2018). a novel optimization of fogging to produce mist in nanoparticles has been developed by Vase and co-workers using electrospraying and ionization of aqueous sanitizers (Vaze et al. 2018, 2019a, 2019b).

Chemical disinfectants can be classified into low-level and high-level disinfectants. low-level disinfectants (LLD) including alcohol (70%), chlorhexidine, iodophor, and sodium hypochlorite can destroy vegetative bacteria and enveloped viruses, but non-enveloped viruses and endospores are less susceptible. In contrast, high-level disinfectants (HLD), including aldehydes, hydrogen peroxide, super-oxidized water, chlorine dioxide, and peracetic acid, can destroy all vegetative bacteria and viruses. With prolonged exposure to HLD, they can also terminate spores. Thus they can be used as sterilizers (Wilson and Nayak 2019).

Alcohol-containing disinfectants Alcohols disinfect vegetative pathogens by interacting with germs' membrane protein and by disrupting their lipid bilayers. The power of alcohol's disinfection is linked with the number of carbons in the alcohol. The reason is that the volatility of alcohol that decreases as the number of carbons increases, leading to increasing the contact time of alcohol with microbes. Besides, the toxicity effect of the alcohol increases as the alcohol molecular weight increases (Wilson et al. 2015).

It is noteworthy that ethanol at a concentration of (mostly 70%) has been proven an effective disinfectant within 30 s against a broad spectrum of bacterial and fungal species (Fendler et al. 2002). However, it is less efficient against non-enveloped viruses (Blaney et al. 2011; Vogel 2011). On the other hand, pure ethanol is not suitable for disinfection. Many studies reveal that gram-positive bacteria show more resistance to 100% ethanol (Fraise et al. 2008; Godbey 2014; McDonnell 2017).

Chlorine-containing disinfectants Chlorine-containing disinfectants mainly include chlorine gas (Cl_2), sodium hypochlorite (NaClO), and calcium hypochlorite ($Ca(ClO)_2$) (WHO 2006a). Chlorine is widely used for water and wastewater disinfection. However, hypochlorite, principally sodium hypochlorite, is used for surface disinfection in households. The toxicity of sodium hypochlorite is less than other chlorine-containing disinfectants, but it is more corrosive (Emmanuel et al. 2004). Electrostatic sprayer equipment was recently innovated to atomize hypochlorite for higher coverage and better disinfection (Clorox®). Attention must be paid that chlorine-containing disinfectants may react with Natural Organic Matter (NOM) found in water, creating some carcinogenic, genotoxic, cytotoxicity, and antiestrogenic compounds (Wang et al. 2017; Wu et al. 2014; Zhou et al. 2012; Zhou et al. 2019).

Hydrogen peroxide Hydrogen peroxide (H_2O_2), considered an eco-friendly disinfectant because of its splitting into H_2O and O_2, has potent oxidizing properties that can damage DNA and other vital cell components through the hydroxyl radicals (Imlay et al. 1988). Hydrogen peroxide is efficient against bacteria, yeasts, and fungi, but it is less effective towards robust bacterial spores and some molds (Anna et al. 2018; Masotti et al. 2019). The concentration of hydrogen peroxide affects its sporicidal effectivity. Lower concentration makes it ineffective against spores (Rutala and Weber 2014, 2016). Nevertheless, its efficiency against *B. anthracis* spores (Hilgren et al. 2007) and *Bacillus* spores (Majcher et al. 2008) proved at higher concentration and a longer treating time (Boyce et al. 2008; Otter et al. 2009).

Hydrogen peroxide can be applied to disinfect hard surfaces and soft surfaces, textiles, and ambient air. H_2O_2 can disinfect soft hospital privacy curtains (Rutala et al. 2014). Besides, it effectively decontaminated historical cotton textiles without deteriorating the strength parameters (Anna et al. 2018). Fogging hydrogen peroxide can be applied to disinfect air when applied for 16–20 min in a 5–15% concentration (Masotti et al. 2019).

It is noteworthy that the oxidizing properties of hydrogen peroxide make it able to oxidize organic materials that reduce the efficiency of hydrogen peroxide. Thus, pre-cleaning to remove any organic materials is essential (Rogers et al. 2005). In addition, hydrogen peroxide is not compatible with some materials such as nylon, neoprene, some sorts of aluminum, some epoxides (Rutala and Weber 1996), and a prolonged decontamination process followed by a long airing time is needed (Moisan et al. 2013).

Chlorine dioxide Chlorine Dioxide (CD) is a potent oxidizing (2.5 times higher than chlorine gas) gas with high solubility (five times higher than chlorine gas) (Jeng and Woodworth 1990). CD gas can be used at relatively low concentrations (2% chlorine nitrogen gas mixture), at room temperature (between15 and 40 °C), and the atmospheric pressure. However, it needs a relatively high relative humidity to be effective (minimum 65%) (Davies et al. 2011)., the Higher the concentration of CD, the more influential the decontamination (Jeng and Woodworth 1990). However, concentration should not exceed 10% in the air as it can be explosive (Jin et al. 2009). CD gas was used to decontaminate large buildings following the epidemic outbreaks and when microorganisms such as mold were prevalent (Canter 2005; Canter et al. 2005). It is noteworthy that CD is unsuitable for polyvinyl materials, plus its solubility in water and has a bleaching effect on porous textiles (Rogers et al. 2004).

Peracetic acid Peracetic acid (also known as peroxyacetic acid) (PAA) is a highly corrosive weak organic acid with the formula (CH_3CO_3H) composed of acetic acid (CH_3COOH) and hydrogen peroxide (H_2O_2) in an aquas solution(Das 2002).

Commercially, PAA solution comprises approximately 40% peracetic acid, 5% hydrogen peroxide, 39% acetic acid, 1% sulfuric acid, and 15% water, w/w. PAA is a potent oxidant with dominant oxidation potential compared to H_2O_2 but less than sodium hypochlorite and can reduce spore contamination on porous and impermeable surfaces (Hayrapetyan et al. 2020; Hilgren et al. 2007; Portner and Hoffman 1968).

Several studies revealed the PAA sporicidal power. For example, while 23.0% of liquid H_2O_2 and 0.78% of

liquid sodium hypochlorite are required to eliminate *B. anthracis* spores, less than 1% of liquid PAA is needed to achieve the same level of decontamination (Hayrapetyan et al. 2020; Hilgren et al. 2007; Majcher et al. 2008; Wood et al. 2013).

For practical decontamination impact of PAA, surfaces should be dirtless as dirt hamper achieving the required level of decontamination. In addition, relative humidity (RH) of ambient air influences the decontamination effect of PAA. RH values between 40 and 80% are optimum for PAA disinfection performance, prevent PAA condensation, and moderate the corrosivity effect of PAA (Wood et al. 2013). The higher the RH, the more potent the effect on porous and nonporous materials. In contrast, at a low RH, 20% no disinfection activity was found (Portner and Hoffman 1968).

Ozone Ozone is a potent oxidizing agent often used to decontaminate water, wastewater, food, and pharmaceutical industries (Wang et al. 2020). Ozone is relatively cheap and can be produced at 4.2×10^{-7} kg/s by an ozone generator using atmospheric air as a source of oxygen (Coccinella; Masotti et al. 2019).

Ozone is characterized by its short half-life time (about 20 min). After that, it converts back to oxygen. During the active phase of Ozone, it is considered the most destructive oxidizing antimicrobial agent and can oxidize organic matter to decolorize and deodorize water and wastewater. Ozone breaks down the microorganisms into hydrogen and carbon dioxide, which are benign waste products, unlike other decontamination techniques that leave dead microorganisms behind them (Tuttnauer 2017). Ozone is also better than a stream at killing bacteria without deteriorating objects susceptible to heat (Towle et al. 2018). Due to its potent oxidization properties, Ozone is corrosive to metals. However, although Ozone is effective against vegetative bacterial cells, it is less effective against yeasts, molds, and bacterial spores (Masotti et al. 2019). moreover, Ozone is a toxic and flammable gas. In addition, the decontamination process is relatively long, about 3 h, and during the process, the premise should be closed and free of people, and after the process, people can re-enter the room after 20 min(Coccinella).

Sterilization

In a contract to sanitizing and disinfection, sterilization is the highest level of decontamination. Sterilizing destroys vegetative pathogens and all viable microorganisms such as their resistive endospores and eggs. Several physical, chemical, and hybrid methods can achieve sterilization.

Physical methods of sterilization

Physical sterilization methods include dry and moist heat and ionizing radiation such as electron beam (E-beam) radiation, Gamma radiation, X-rays, and Ultraviolet Type C (UVC).

Moist heat sterilization Moist heat sterilization refers to using high-temperature steam to destroy pathogens. The potent of hot steam in sterilization is due to the latent heat released by the steam upon its condensation on inanimate surfaces. This high energy leads to cellular protein denaturation and coagulation, leading to the destruction of microorganisms (Bao et al. 2013). Moist heat sterilization can be achieved by autoclaving, a pressure cooker in which water is boil under pressure at a higher temperature than 100 °C. In autoclaving, moist air is produced at high pressure (15 psi) and (≈121 °C). These extreme conditions kill microorganisms by dehydrating the cell (Fuerst 1983). There are two standard techniques of autoclaving; gravity and pre-vacuum. In gravity autoclaving, steam is pumped into the autoclave, and because steam has less density than air, it displaces air, which is considered an insulator, out of the autoclave chamber by gravity through a drain vent. It Is noteworthy that objects should be nonporous materials such as glassware, tools, waste, and utensils in gravity autoclaving.

In contrast, pre-vacuum autoclaving allows air to be removed first by a vacuum pump. This step allows steam to penetrate porous areas of the objects that could not be approached by the gravity method (Sandle 2013b; Trapotsis 2020). Pre-vacuum autoclaving demonstrated higher efficiency in microbial decontamination than gravity (Winter et al. 2017). Large pieces of equipment that cannot be loaded into an autoclave or those located in a fixed place can (e.g., vessels, valves, process, and production lines) be sterilized by steam-in-place (SIP) units that use purified water to generate clean steam at 121 °C for at least 30 min sterilizing the objects (Cole 2006; McClure 1988). Recent SIP units generate steam at150 °C and 5 bars, while others allow the addition of a hydrogen peroxide solution in the steam jet to maximize the power of sterilization of steam (SANIVAP).

Moist heat sterilization is beneficial in nontoxicity, availability, rapidity, and efficacy. However, it has some deleterious effects on some materials, such as corrosion to metallic tools and deterioration and disfiguration of heat-sensitive materials such as low-density polymers and lubricants (Bucx et al. 1999; Sureshkumar et al. 2010).

Dry heat sterilization While moist heat sterilization is done by transferring latent heat from the steam to the object, dry heat sterilization is done by conduction heat

transfer through the object's exterior surface. Like steam sterilization, dry heat coagulates the proteins causing oxidative free-radical damage and eventually the drying of cells.

Dry heat sterilization can be performed by direct flame or incineration. Direct flame is commonly used for sterilizing needles and inoculating loops, where an item should be subjected to direct flame until it has a red glow. Incineration is another effective way to sterilize disposable items and biological samples, in which dry air is produced at a very high temperature up to 1500 °C in a furnace oven. This method, in general, can safely destruct hazardous waste, as it turns objectives into a rash. Modern incinerators filter out pollutants allowing only clean air to be released from the machine (Lee and Huffman 1996; Wang et al. 2020).

Ionizing radiation and ultrasonic Irradiation is considered an excellent sterilization method. Radiation uses ionizing electromagnetic radiation such as electron beam (E-beam) radiation, Gamma radiation, X-rays, and Ultraviolet Type C (UVC). These types of radiation have very short wavelengths, high frequency, and high energy that can destroy all viable microorganisms and viruses.

E-beam and gamma radiation Gamma and E-beam radiations are the most energetic as they effectively kill vegetative pathogens and endospores. E-beam radiation delivers a higher radiation dose than Gamma radiation, penetrating less deep. Meanwhile, Gamma radiation can penetrate about 50 cm of the layers, E-beam radiation can only penetrate about 5 cm. Gamma radiation at over 25,000 Gray is ideal for sterilizing disposable items. However, its role in the sterilization of reusable tools are limited (Wilson and Nayak 2019), in addition to strict protection requirements of place and code of dress of operators (Sureshkumar et al. 2010).

Ultraviolet radiation type C The ultraviolet radiation type C (UVC) is also known to have a sterilization effect on viruses and bacteria with a germicidal effect of 200–365 nm for air or surface (Wang et al. 2009; Zhao et al. 2013). UVC destroys microorganisms by inactivating RNA/DNA by forming pyrimidine dimers from thymine and cytosine due to the mutagenic DNA lesions that occurred by UVC absorption (Nerandzic et al. 2014; Owens et al. 2016; Sinha and Hader 2002). UV radiation is considered an affordable and efficient sterilization method over thermal and chemical methods, usually conducted at ambient temperature and pressure(Chen et al. 2010).

It is noteworthy that viruses are more susceptible to be inactivated by UVC rather than bacteria that tolerate UVC due to the presence of the cell wall (Chang et al. 1985; Jensen 1964; Knudson 1986; Ko et al. 2002; Koch 1946; Riley et al. 1976). Using ultraviolet irradiation to purify and sterilize air has received significant consideration (Ijaz et al. 2016; Lin and Li 2010; Mphaphlele et al. 2015; Sattar et al. 2016) because of its quickness, efficiency, safety and cost-effectiveness (Escombe et al. 2009).

In addition to using UVC to sterilize air, there is a growing interest in UVC to kill a wide range of microorganisms and extend the life of food products such as juices (Koutchma et al. 2016; Rodriguez-Gonzalez et al. 2015). Sterilization of food products is limited when applied to turbid and colored liquid that retard and hampers UV penetration (Gayán et al. 2014; Koutchma et al. 2016).

There are two primary sources for UVC; low-pressure mercury vapor UVC lamp (UV-MV) and ultraviolet light-emitting diode sources UV-LEDs. UV-MV is the traditional source of UVC radiation, but it contributes only 30% of the UVC power needed. In addition, it involves a safety concern as Ozone is the side product of UV-MV (Miller et al. 2013; Zhang et al. 2011). Alternatively, UV-LEDs is safer and more effective than UV-MV to disinfect indoor airborne pathogens (Nunayon et al. 2020).

Ultrasonic Ultrasonic is a recent promising method of sterilization(Chemat et al. 2011; Lin et al. 2019; Piyasena et al. 2003; Sango et al. 2014). Ultrasonic has been proved a highly efficient approach for sterilization at 300–600 W under the sound intensity of 28 kHz for 10–30 min, leading to cavitation effect in microbial cells (Lin et al. 2019; Sarkinas et al. 2018).

Chemical methods of sterilization

Gas forms of chemicals such as ethylene oxide (EtO) dominate sterilization. Furthermore, prolonged exposure to high-level disinfectants (HLD) such as hydrogen peroxide, chlorine dioxide, and peracetic acid can terminate spores. (Solon and Killeen 2019; Wilson and Nayak 2019). Ethylene oxide (EtO) is a cold gas sterilizer used for sterilizing electronic surgical equipment and other medical stuff that cannot be sterilized by autoclave. Although EtO is effective in sterilization, it is lethal at toxic levels, flammable, explosive, expensive, and reacts with water to produce antifreeze compound "ethylene glycol." (Sureshkumar et al. 2010). The toxicity effect of EtO can be mitigated by aeration of the objects before their use (Moisan et al. 2013). It is noteworthy that EtO is less effective against fungi (Anna et al. 2018).

Hybrid physical–chemical cold plasma method of sterilization

Plasma is known as the fourth state of matter, and it refers to ionized gas produced by Radiofrequency (RF) (Brandenburg et al. 2007), laser, or microwave (Pipa et al. 2012). Plasma is composed of gas atoms, ions, electrons, and photons (Hertwig et al. 2015; Silveira et al. 2019). When these gas species are found in non-thermodynamic equilibrium, the plasma is known as non-thermal or cold plasma (CP), but it is known as thermal or hot plasma when they are found in equilibrium.

CP has been verified as an effective sterilization method of pathogens such as bacteria, viruses, yeast, and molds adhering to packing polymer surfaces with no effect on their bulk properties. Thus it shows more resistance in treated packed food (Muranyi et al. 2007; Zhao et al. 2020). However, the ability of CP to inactive spores mainly depends on the type of used gas (Purevdorj et al. 2003; Stapelmann et al. 2013), voltage, exposure time, and the relative humidity (Patil et al. 2014). CP is widely used in food industries, biomedical devices, and biological materials (Misra et al. 2016; Zhang et al. 2019).

The potent decontamination effect of the CP is due to the produced broad range ultraviolet (UV) wavelengths by plasma (Moisan et al. 2013), in addition to the potent oxidative properties of reactive oxygen species that peroxide cell lipid, inactivate enzymes, and cleave DNA (Han et al. 2014; Sureshkumar et al. 2010).

It is noteworthy that reactive species in plasma have the most significant contribution to decontamination. Thus it is expected that a high plasma density promotes decontamination efficiency. However, it increases the temperature of the treated surface simultaneously (Mackinder et al. 2020). For example, using argon gas for the cold plasma can sterilize the object in 15 min (Hertwig et al. 2015), But oxygen gas-based plasma can sterilize the object in 3 min (Zhao et al. 2020).

Hydrogen peroxide gas can also be used in cold plasma for destroying a broad spectrum of germs, such as bacteria, spores, viruses, fungi, and yeast (Block 2001; Heckert et al. 1997) because of hydroxyl radicals that can damage cell components, like proteins, lipids, and DNA (Russell 1990). Moreover, it is characterized by its nontoxicity and relatively short cycle times (about 75 min) (Veerabadran and Parkinson 2010). Although it is most commonly used to sterilize food packaging material (Kirchner et al. 2013), it is less effective for medical equipment (Wilson and Nayak 2019).

Evaluation of decontamination methods

Decontamination methods are generally evaluated for efficacy, effectiveness, and efficiency. Efficacy measures the treatment's ability to achieve the desired effect under "ideal" controlled circumstances (such as in a laboratory experiment, i.e. 'in Vitro'). In layman's terms, efficacy measures whether the decontamination method works or not. Effectiveness measures the treatment's ability to achieve the desired effect under "real" circumstances (in healthcare practice, i.e. 'in vivo'). In other words, effectiveness measures whether the decontamination method works within the intended setting. Efficiency evaluates the treatment concerning the resources it consumes, so it measures whether the decontamination method is a good value (Haynes 1999; Marley 2000). Table 2 and Fig. 2 summarize microbial decontamination methods, effectiveness, and applications.

Monitoring of decontamination methods

Biological and chemical indicators are used to monitor the lethality of a sterilization process and ensure the effectiveness of sterilization. They are also used to routinely monitor a sterilizer's performance according to practices developed and published by the "Association for the Advancement of Medical Instrumentation" (AAMI), the "Association for peri-Operative Registered Nurses" (AORN), and the "Centers for Disease Control" (CDC).

Biological indicators (BI) contain many highly resistant spores of *Geobacillus stearothermophilus*. Destroying and killing these spores in the BI using the tested sterilization processes implies that the sterilization process effectively kills other potential pathogens. BIs are commercially available as test kits, and they are used to assess the sterility level of water, food containers, and medical and surgical tools and instruments in hospital rooms. When the test kit is incubated, the spores of *G.Stearothermophilus* germinate, producing α-glucosidase enzymes that react with the fluorescent media (4-methyl-umbelliferyl-α-D-glucopyranoside) in the kit and produces a fluorescent signal, which is then detected by the detector in the incubator. The advantage of BIs is that they are pretty quick tests, only requiring 20 min for both incubation and detection (BSI 2014a; ANS 2017; Gordon 2013; Swenson 2012).

In contrast to BIs, chemical indicators (CIs) do not contain resistant spores and instead use special chemicals or pigments that change physical properties or color when specific environmental conditions have been attained. As such, they can monitor decontamination methods based on the fulfillment of one or more of the parameters required for a satisfactory sterilization process. This physical or chemical change is interpreted as a pass or fail result. For example, when using steam for sterilization, such as in an autoclave, a solid CI that converts to liquid upon exposure to steam can be used to confirm the quality of sterilization. When pigments are used, they chemically react with some critical parameters

Table 2 Summary of microbial decontamination methods, effectiveness, and applications

Decontamination category	Decontamination method	Microbial effectiveness	Application	References
Cleaning	Cleaning removes dust, dirt, and organic matter from surfaces but does not remove any microorganisms	None	The importance of cleaning is removing any materials that can interfere with the sanitizer's effectiveness	Rutala and Weber (2014)
Sanitizing	Applying diluted detergent followed by rinsing with clean water and drying	Reducing the microbial populations to a sanitary level	Washing hands, clothes, tools, and equipment	Veerabadran and Parkinson (2010)
Disinfection	Physically by solar Energy: direct surface contact with solar radiation at 40 °C	Vegetative bacteria, including *V. cholerae* and *E.coli*	Water and solid surfaces	Berney et al. (2006), McGuigan et al. (1998)
Disinfection	Physically by dry heat: using a forced convection oven at a temperature of 160 °C for 2 h or 170 °C for 1 h	Vegetative bacteria, including pathogens	Heat-resistant inanimate objects such as glass and metal	Joslyn (2001)
Disinfection	Physically by moist Heat: By immersing the objective in hot water of temperatures ranging from 80 to 100 °C for 60–600 s	Vegetative bacteria, including pathogens	Inanimate objects. However, repeated heat exposure may reduce some objects' function over time; especially those are made of plastic components	Collins et al. (2019), McDonnell (2017)
Disinfection	Physically by moist heat by pasteurization: (HoP) at (62.8–68.3 °C) for 30 min (HTST) at (71.7 °C) for 15 s (HHST) at (88.3–100 °C) for (15–0.01 s) (UHT) at (135–150 °C) for (2–15 s) In-container sterilization at 116 °C for 20 min	Vegetative bacteria, including pathogens	Milk, egg nog, and frozen, cream, dessert mixes, and cans	Al-Attabi et al. (2009), ChemViews (2012), Ciochetti and Metcalf (1984), Deeth and Datta (2011), Wright (2019)
Disinfection	Physically by infrared irradiation FIR for surface decontaminations NIR for bulk decontamination	Vegetative bacteria and fungi	Food products such as cereals, nuts, shell eggs, and fruits	Alkaya et al. (2016), Bingol et al. (2011), Hamanaka et al. (2011), Wang et al. (2014)
Disinfection	Physically by microwave and radiofrequency radiation	Vegetative bacteria and fungi	Food materials	Dev et al. (2012), Vijay et al. (2021)
Disinfection	Physically by ultraviolet type-B radiation	pathogenic bacteria	Drinking water	Mbonimpa et al. (2012)
Disinfection	Chemically using alcohols: ethanol at a concentration of (mostly 70%) for 30 s	Viruses, fungi, and vegetative bacteria, including pathogens	Inanimate objects	Fendler et al. (2002)
Disinfection	Chemically using chlorine-containing disinfectants	Viruses, fungi, and vegetative bacteria, including pathogens	Chlorine is widely used for water and wastewater disinfection Hypochlorite, principally sodium hypochlorite, is used for surface disinfection in households	Emmanuel et al. (2004), WHO (2006a)

Table 2 (continued)

Decontamination category	Decontamination method	Microbial effectiveness	Application	References
Disinfection	Chemically using hydrogen peroxide 7% of liquid H_2O_2 for 15 min inactivated 6 LR of Bacillus spores Fogging hydrogen peroxide can be applied to disinfect air when applied for 16–20 min in a 5–15% concentration	Viruses, yeast, fungi, and vegetative bacteria, including pathogens	Hard surfaces and soft surfaces, textiles, and ambient air. However, it is not compatible with some materials such as nylon, neoprene, some sorts of aluminum, and epoxides	Majcher et al. (2008), Masotti et al. (2019), Rutala and Weber (2014, 2016)
Disinfection	Chemically using chlorine dioxide at low concentrations (2% chlorine nitrogen gas mixture), room temperature (between15 and 40 oC), at atmospheric pressure, and high relative humidity to be effective (minimum 65%)	Viruses, yeast, fungi, molds, and vegetative bacteria, including pathogens. Endospores at prolonged exposure	Inanimate objects Decontamination of large buildings following the epidemic outbreaks and when microorganisms such as mold were prevalent	Canter (2005), Canter et al. (2005), Davies et al. (2011)
Disinfection	Chemically using peracetic acid at low concentrations (1% of liquid PAA) and high relative humidity (minimum 60%). Surfaces should be dirtless	Viruses, yeast, fungi, molds, and vegetative bacteria, including pathogens. Endospores at prolonged exposure	Porous and impermeable surfaces	Hayrapetyan et al. (2020), Hilgren et al. (2007), Majcher et al. (2008), Portner and Hoffman (1968), Wood et al. (2013)
Disinfection	Chemically using Ozone for 3 h, and during the process, the premise should be closed and free of people, and after the process, people can re-enter the room after 20 min	Effective against vegetative bacterial cells, but it is less effective against yeasts, molds, and bacterial endospores	Porous and impermeable surfaces Better than a stream at killing bacteria without deteriorating objects susceptible to heat	Coccinella; Masotti et al. (2019), Towle et al. (2018), Tuttnauer (2017)
Sterilization	Physically by moist heat by autoclaving at high pressure (15 psi) and (≈121 °C). Autoclaving includes gravity and pre-vacuum methods	Viruses, yeast, fungi, molds, vegetative bacteria, and endospores	Gravity autoclaving for non-porous objects Pre-vacuum autoclaving for porous objects	Sandle (2013b), Trapotsis (2020), Winter et al. (2017)
Sterilization	Physically by moist heat by Steam-in-Place (SIP) at 121 °C for at least 30. Sterilization power can be maximized by the addition of a hydrogen peroxide solution	Viruses, yeast, fungi, molds, vegetative bacteria, and endospores	Large pieces of equipment that cannot be loaded into an autoclave or those located in a fixed place can (e.g., vessels, valves, process, and production lines)	Cole (2006), McClure (1988), SANIVAP
Sterilization	Physically by dry heat by direct flame or incineration at a very high temperature (1500 °C) in a furnace oven	Viruses, yeast, fungi, molds, vegetative bacteria, and endospores	Direct flame for needles and inoculating loops Incineration for hazardous wastes and biological samples	Lee and Huffman (1996), Wang et al. (2020)
Sterilization	Physically using E-beam and Gamma radiation	Viruses, yeast, fungi, molds, vegetative bacteria, and endospores	Ideal for sterilizing disposable items. However, its role in the sterilization of reusable tools are limited	Wilson and Nayak (2019)

Table 2 (continued)

Decontamination category	Decontamination method	Microbial effectiveness	Application	References
Sterilization	Physically using ultraviolet radiation type C (UVC) at 200–365 nm	viruses are more susceptible to be inactivated by UVC rather than bacteria that tolerate UVC due to the presence of the cell wall	Air and food products such as juices	Koutchma et al. (2016), Rodriguez-Gonzalez et al. (2015), Wang et al. (2009), Zhao et al. (2013)
Sterilization	Physically using ultrasonic waves at 300–600 W under the sound intensity of 28 kHz for 10–30 min	Viruses, yeast, fungi, molds, vegetative bacteria, and endospores	Porous and impermeable surfaces	Chemat et al. (2011), Lin et al. (2019), Piyasena et al. (2003), Sango et al. (2014), Sarkinas et al. (2018)
Sterilization	Chemically using ethylene oxide (EtO); applied as a cold gas	Viruses, yeast, vegetative bacteria, and endospores, but less effective against fungi	Electronic surgical equipment and other medical stuff that cannot be sterilized by autoclave	Anna et al. (2018), Moisan et al. (2013), Sureshkumar et al. (2010)
Sterilization	Using hybrid physical–chemical cold plasma using argon, oxygen, or hydrogen peroxide gases for 3–15 min	Viruses, yeast, fungi, molds, vegetative bacteria, and endospores	Most commonly used for sterilization of food packaging material	Block (2001), Heckert et al. (1997), Hertwig et al. (2015), Kirchner et al. (2013), Zhao et al. (2020)

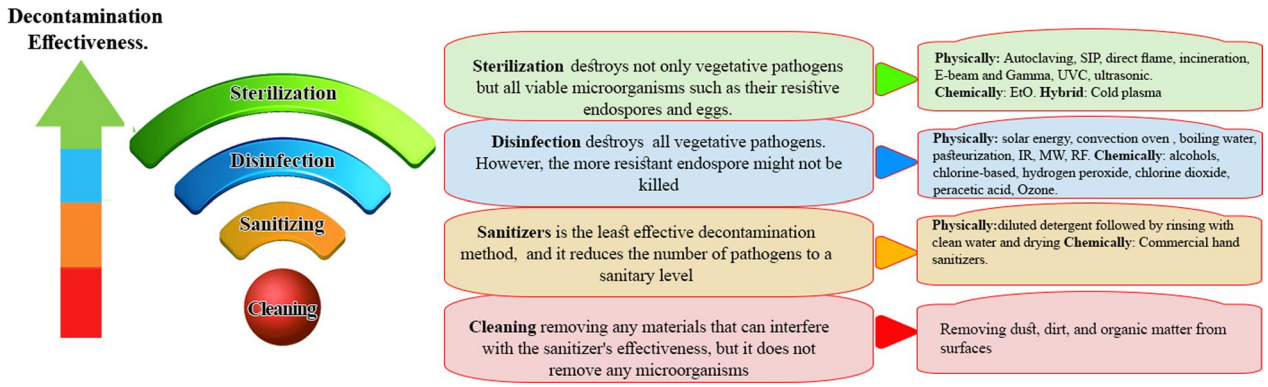

Fig. 2 Summary of microbial decontamination methods, effectiveness, and applications

of the sterilization process, and consequently, the color changes to its endpoint color, indicating that the parameters for sterilization have been met. (BSI 2001, 2014b; ANS 2017).

Assessing the decontamination methods

The level of decontamination can be assessed using "D", "LR", and "SAL" values. D-value is an abbreviation of "decimal reduction time" (DRT) and is used to assess a method or technology that is capable of inactivating 90% of the population of the microorganisms in a test (Conley 2014a). The method or technology measurement can be a time, a temperature, a pressure, a chemical, a dose, or a technique. For example, if a pressure of 2 bar results in a *D*-value of 0.5 min, this means that 0.5 min of 2 bar pressure is sufficient to inactivate 90% of microorganisms in that test. It should be noted that *D* values are measured on a logarithmic scale, and 90% decontamination is referred to as a 1-log reduction (1 LR). This means 2-log reduction (2 LR) indicates a 99% reduction of the microbial population, 3 LR means 99.9% reduction.

Although decontamination of 99.9% of microbes seems notable, this percentage means that thousands of pathogens might still survive. Thus, it is helpful to consider another assessment measure, SAL, which stands for Sterility (or Security) Assurance Level (Lerouge 2012; Wilson and Nayak 2019). SAL measures the number of remaining contaminated items among those which have undergone decontamination (Conley 2014b). In other words, the SAL is the probability of a non-sterile unit or surviving microorganism after the sterilization process. The required assurance of sterility is typically a SAL of 10^{-6} (Enzinger 1990; Wilson and Nayak 2019), which means that one might remain unclean for every million units undergoing sterilization. Achieving a SAL of 10^{-12} is considered overkill (Sandle 2013b).

Although both SAL and LR values use a logarithmic base of 10, it is imperative to emphasize that the SAL is not the exact measurement as the LR. In other words, a value of 6 LR does not necessarily equate to a SAL of 10^{-6}. Indeed, the value of total LR required to achieve a SAL of 10^{-6} is a summation of both the LR required to have a population of one unit, and a further 6 LR is required to achieve a SAL of 10^{-6}. For example, a 6 LR results in one microorganism remaining for a population of one million microorganisms. Additionally, the probability of having one surviving microorganism for every million units is a SAL of 10^{-6}. Thus the total LR is 10^{-12}, as shown in Fig. 3.

Another example to explain the calculation is; if a *D*-value (i.e., 1 LR) for a microbe is about 20 s for specific decontamination conditions, then, after exposure to the same conditions for two minutes (120 s), the microbial decontamination will reach 6 LR, and consequently, four minutes of decontamination are needed to reach a 12 LR, which is equivalent to a SAL of 10^{-6}. A further example is: if a decontamination method results in 2 LR (99% decontamination), which results in 1 colony-forming unit (CFU) remaining from an initial CFU of 100 within 60 s; to achieve a SAL of 10^{-6}, the total LR for both microbial reduction and sterility assurance level values must be added together (i.e.$2+6=8$). Thus $8*60$ s or 8 min are required. Understanding the concepts of these calculations is very important in order to be able to assess decontamination levels correctly.

Another helpful test dedicated to assessing a chemical decontamination method is Breakthrough Survival (BTS), which measures the failure of a chemical biocide to kill 10^6 vegetative organisms within 1 min. This time duration was chosen as the expected time for a chemical biocide to dry once applied to an inanimate surface (Rutala et al. 2006).

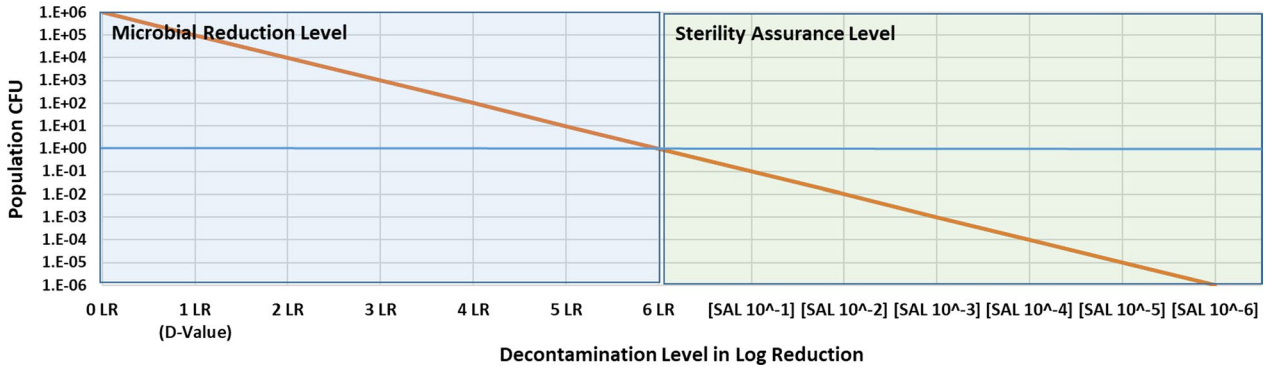

Fig. 3 Level of decontamination regarding log reduction (LR) and sterility assurance level (SAL) measures

Conclusions

This work comprehensively reviewed the recent trends of microbial decontamination approaches for occupational, industrial, and domestic applications to help choose, design, and optimize the appropriate decontamination method to achieve the required level of decontamination. Sanitizing is the least effective decontamination method that reduces the number of pathogens to a sanitary level. Disinfectants and antiseptics provide a higher level of decontamination, as they inactivate or kill vegetative microbes. The best decontamination method is sterilizing, killing vegetative microbes and their spores. These methods can be classified into physical, chemical, or hybrid methods with different scopes and applications. The level of decontamination can be monitored and assessed to evaluate the lethality of decontamination and ensure the effectiveness of the process.

Abbreviations

AAMI: Association for the advancement of medical instrumentation; AORN: Association for peri-operative registered nurses; BI: Biological indicators; CDC: Centers for disease control and prevention; CDC: Centers for disease control; CI: Chemical indicator; CMA: Canadian medical association; DRT: Decimal reduction time"; EPA: Environmental protection agency; EtO: Ethylene oxide; FIR: Far-infrared; HEPA: High-efficiency particulate air; HLD: High-level disinfectants; HVAC: Heating, ventilating, and air-conditioning; LLD: Low-level disinfectants; LR: Log reduction; MERV: Minimum efficiency reporting values; NIR: Near-Infrared; NOM: Natural organic matter; PAA: Peracetic acid; RF: Radiofrequency; SAL: Sterility (or security) assurance level; UV: Ultra violet; UV-LED: Ultraviolet light-emitting diode sources; UV-MV: Low-pressure mercury vapor UVC lamp.

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The authors declare that the manuscript complies with the research publication ethics. It does not report on or involve the use of any animal or human data and does not contain data from any person.

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