

# Comprehensive Review on Sterilization Methods and Material Considerations

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## Abstract

*The problem of environmental contamination, which is important for both public health and the economy, has been addressed through a great deal of research on the sterilization and disinfection of pollutants and microorganisms. Many types of pollutants and hazardous materials, such as microorganisms and toxic gases, are discharged into the environment and can enter the human body through ingestion, adsorption, or inhalation. Numerous respiratory conditions, strokes, lung cancer, and heart problems linked to these pollutants increase the mortality rate among humans. Therefore, in order to save lives, it is imperative to control environmental pollution by using cost-effective and efficient sterilization and disinfection techniques. Along with more sophisticated methods, there are many types of conventional physical and chemical sterilization and disinfection treatments, including ethylene oxide, ozone, hydrogen peroxide, radiation, filtration, dry and moist heat, and more. Suggested both traditional and cutting-edge methods of disinfection and sterilization, along with their applications and mechanisms of action. Even though advanced sterilization and disinfection technologies provide an effective solution, combined sterilization and disinfection technologies have been shown to be a more effective innovation for protecting both indoor and outdoor environments. Nowadays, the importance of sterilization and disinfection for human health is a major concern because of the COVID-19 pandemic. For these methods, people are receiving a lot more attention. Natural resources have been drastically depleted in recent years due to the fast urbanization and industrialization processes, which include mining, transportation, manufacturing, construction, and petroleum refining.*

**Keywords:** Sterilization, disinfection, environmental contamination, public health, hazardous waste

## INTRODUCTION

The proportionate rise in the quantity and number of hazardous wastes is also attributable to the same cause. As a result of pollution, these wastes are constantly posing a threat to the quality of the air, soil, and water. Hazardous materials are released into the environment in a variety of ways, including suspended airborne particles, toxic gases (such as sulfur oxides, ozone, carbon oxide, and nitrogen oxides), and volatile organic compounds (VOCs). However, contaminants like organic materials, heavy

metals, and microbial pathogens that have a significant negative impact on human health can be found in soil and water. Inhalation, adsorption, or ingestion are the three ways that these environmental contaminants can enter the human body. Additionally, certain pollutants have the ability to group together in food chains. Biomedical waste (BMW) is another significant source of pollutants in addition to the ones mentioned above. BMW is typically produced by biological research activities as well as medical procedures like disease diagnosis, treatment, and vaccination. BMW also includes patient excretion of medications that are high in chemical and pharmaceutical residues, as

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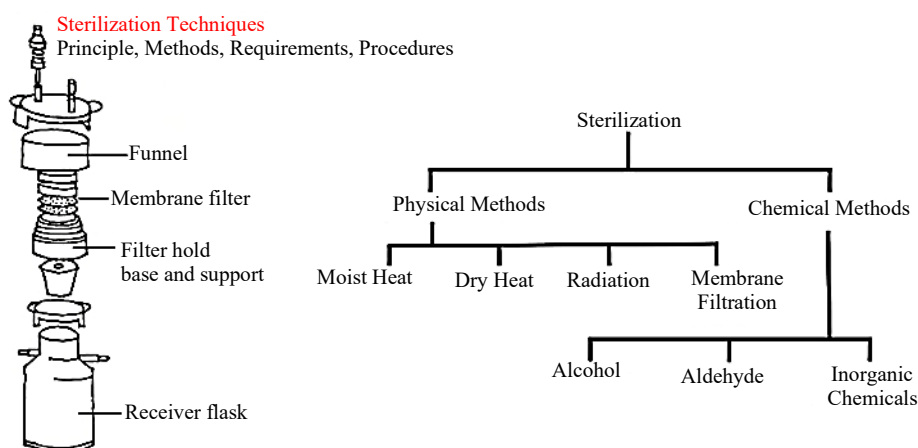
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well as the active ingredients of drugs and their metabolites. However, 15% of BMW is classified as infectious hazardous waste, and the remaining 85% is classified as non-hazardous waste. Because hazardous BMW is a host to a number of pathogenic microorganisms, improper removal poses serious risks to both the environment and public health. If these harmful microbes are not controlled, they may infiltrate the human body. Hemorrhagic fevers, bacteremia, influenza, viral hepatitis, respiratory, gastrointestinal, and skin infections are among the most frequent infections brought on by BMW. According to studies, the prevalence of virus infections among BMW collectors is higher in Brazil, Greece, India, Iran, and Pakistan. Infectious microorganisms are carried by medical devices used for patient diagnosis and treatment. An estimated 1.7 million patients in the US are thought to be impacted by HAIs, which also cost the healthcare system roughly \$9.8 billion. Additionally, HAIs negatively impact patients' health, well-being, and quality of life; however, severe HAIs can also result in sepsis, a potentially fatal organ dysfunction. Every year, the United States alone reports roughly 750 000 cases of sepsis, which costs the healthcare system more than \$20 billion. The aforementioned situation thus emphasizes the necessity of sterilization and disinfection methods for BMW. In recent years, the hygiene concept has come to understand the basis for the detonation in various chemical-based products. Quaternary ammonium compounds showed increased activity and changed chemistry, while peroxygen compounds garnered a lot of interest due to their superior *in vitro* activity. The rise in products containing microbicides has sparked a serious worry about the improper application of chemical disinfectants. Chemical agents known as microbicides are used in a variety of applications, such as the healthcare, water, food, consumer goods, and manufacturing sectors, to control or eradicate microorganisms. Therefore, to control the microorganism in liquids, gases, or on surfaces, both sterilization and disinfection are used. Their use has significantly reduced the incidence of infectious diseases such as gastroenteritis, pneumonia, and illnesses acquired through medical treatment [1].

Sterilization is a critical process in microbiology, healthcare, and laboratory settings to eliminate or destroy all forms of microbial life, including bacteria, viruses, and spores. The image illustrates different sterilization techniques categorized into physical and chemical methods. Physical methods include moist heat, dry heat, radiation, and membrane filtration, each with specific applications depending on the materials being sterilized. Chemical methods involve the use of alcohols, aldehydes, and inorganic chemicals to disinfect and sterilize surfaces, instruments, and biological samples. Additionally, the diagram on the left represents a filtration-based sterilization setup, showing a funnel, membrane filter, filter holder, and receiver flask, commonly used for sterilizing heat-sensitive liquids. These techniques play a vital role in ensuring sterility and safety in medical, pharmaceutical, and research environments (Figure 1). Proposed using medical plastic waste to produce alternative fuels. The primary source of the environmental risks and infection threat in recent years has been the disposal and burning of medical plastic waste in dumping yards. The ecosystem may be greatly enhanced by implementing appropriate waste management practices and the right technology, [2] such as the 5R's (refuse, reduce, reuse, repurpose, and recycle).



**Figure 1.** Sterilization techniques – principle, methods, requirements, and procedures.

Furthermore, the 5R's is a comprehensive strategy that can be used for government enforcement mandates and regulations or stakeholder awareness. To address waste management through advanced technology, this review explores a promising approach to converting medical plastic waste into drop-in fuel and other valuable products. Pyrolysis emerges as a key method due to its efficiency, lower environmental impact, and minimal pollutant emissions. Studies indicate that COVID medical waste management (CMWM) technology can yield approximately 70–80% plastic pyrolysis oil (PPO), 10–15% bio-char, and a portion of gaseous fuel. According to ASTM standards, PPO has potential as a viable feedstock for compression ignition (CI) engine fuel. This study contributes to improving medical waste management infrastructure in an environmentally sustainable manner while providing an effective solution for handling COVID-related waste.

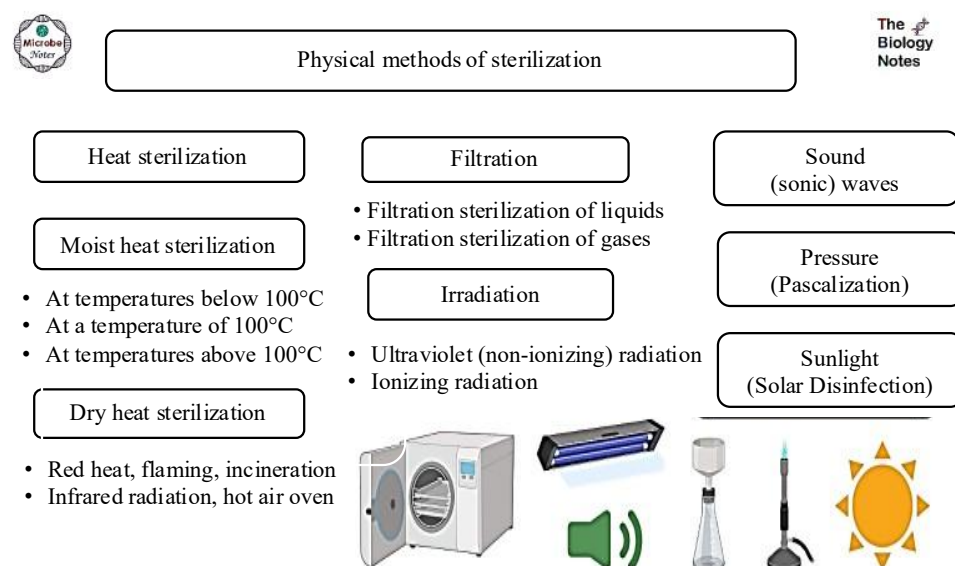
Waste is broadly defined as any material discarded after serving its primary purpose or deemed damaged, unusable, or without value. The Basel Convention categorizes waste as substances or objects that are discarded, intended for disposal, or legally required to be disposed of. Medical plastic waste specifically refers to plastic waste generated by hospitals, healthcare facilities, medical laboratories, and biomedical research centers. Small-scale medical waste sources are also included in this classification. The United States Environmental Protection Agency (USEPA) offers a more detailed definition, identifying medical plastic waste as hospital or clinical waste contaminated by blood, bodily fluids, or other infectious materials.

The growing volume of medical plastic waste presents a significant challenge to waste management systems, an issue exacerbated by the COVID-19 pandemic. On January 30, 2020, the World Health Organization (WHO) declared COVID-19 a public health emergency, prompting governments worldwide to implement various safety measures to limit its spread. As a result, the widespread use of face masks, face shields, personal protective equipment (PPE), and gloves has surged, leading to an unprecedented increase in plastic waste from both medical and public sources. The global healthcare sector continues to grapple with the dual burden of managing infectious disease outbreaks while addressing the environmental consequences of escalating plastic waste.

Sterilization is an essential process in microbiology and healthcare to eliminate or deactivate microorganisms. The image categorizes various physical methods of sterilization, including heat sterilization, filtration, irradiation, sound waves, pressure (Pascalization), and sunlight (solar disinfection). Heat sterilization is divided into moist heat and dry heat sterilization, where moist heat involves sterilization at different temperature levels, while dry heat includes methods like flaming, incineration, and the use of hot air ovens. Filtration is used for sterilizing liquids and gases, making it crucial for heat-sensitive materials [3]. Irradiation includes ultraviolet and ionizing radiation, effectively killing microbes in controlled environments. Additional methods such as sonic waves, pressure-based sterilization, and solar disinfection also contribute to microbial inactivation. These techniques are widely used in medical, laboratory, and industrial applications to maintain sterility and prevent contamination (Figure 2).

The rapid surge in plastic consumption has emerged as a major environmental concern. The widespread use of personal protective equipment (PPE) and other disposable plastic items during the COVID-19 pandemic has intensified global waste management challenges, causing disruptions in supply chains and increasing issues related to waste disposal. The rising demand for essential medical plastics, including PPE kits for healthcare workers, masks, gloves, life-support system components, and syringes, mirrors the pandemic's global trajectory.

According to a 2017 report from the United Nations Environment Programme (UNEP), global plastic waste production stands at approximately 400 million tonnes annually. The COVID-19 crisis has further amplified this issue, significantly increasing medical plastic waste. For instance, in February 2020, China ramped up the daily production of single-use face masks to 116 million—over twelve times its usual output—to meet the growing demand for protective gear among healthcare workers, service providers, and the general public [4].



**Figure 2.** Physical methods of sterilization – techniques and applications.

Plastics play a crucial role in modern society, particularly in public health and medicine, due to their resistance to chemical, physical, and biological degradation. The affordability and versatility of plastics have enabled mass production of essential single-use medical items, making them indispensable in healthcare. However, the downside of plastic usage is the accumulation of vast amounts of plastic waste in landfills and the environment. Plastics account for roughly 10% of municipal waste by weight, and their improper disposal leads to severe ecological consequences. Reports indicate that plastic waste is now found in diverse natural environments, including remote mountain peaks, marine ecosystems, and agricultural lands.

Microplastics have been detected in soil, often introduced through the transfer of sewage sludge, while plastic and glass fragments have been found contaminating compost derived from waste. Rainfall and floods contribute to plastic pollution by washing debris into waterways, rivers, and oceans. Despite the urgent need for more research into the impact of plastic waste on terrestrial and aquatic ecosystems, the harmful effects of plastic additives on the environment and human health are well-documented. Certain chemicals, such as bisphenol A (BPA) and phthalates used in plastic production, have been linked to serious health risks. Additionally, polyhalogenated flame retardants, especially polybrominated diphenyl ethers (PBDEs), have raised environmental and toxicological concerns.

The table categorizes different indicators used in gaseous sterilization methods based on their principles, devices, and monitored parameters. Physical indicators rely on temperature recording charts to monitor sterilization temperature [5]. Chemical indicators function through different principles, such as reactive chemicals, the capillary principle, and temperature-sensitive chemicals. These indicators use impregnated indicator paper, wick migration, and temperature-sensitive wax to monitor gas concentration, temperature, and exposure time. Biological indicators involve temperature-sensitive microbes like *Bacillus subtilis* to assess sterilization effectiveness, with the D value serving as a key parameter. These indicators ensure proper sterilization validation in medical, laboratory, and industrial settings (Figure 3).

Plastics' molecular structure makes them highly resistant to degradation, prolonging their presence in the environment. When improperly managed, plastic waste clogs rivers, obstructs drainage systems, and pollutes reservoirs, exacerbating environmental contamination. Without effective waste management strategies, the persistent nature of plastics will continue to pose ecological and health risks on a global scale [6].

Indicators	Sterilization methods	Principle	Device	Parameter monitored
Physical	Gaseous	Temperature recording charts	Temperature recording charts	Temperature
Chemical	Gaseous	Reactive chemical	Indicator paper impregnated with reactive chemical.	Gas concentration, Temperature, Time
		Capillary principle	Based on same migration along wick principle	Gas concentration, Temperature, Time
		Temperature sensitive chemical	A temperature sensitive white wax concealing a black marked	Temperature
Biological	Gaseous	Temperature sensitive microbes	Bacillus subtilis	D value

**Figure 3.** Types of indicators used in gaseous sterilization methods.

Plastic pollution in marine ecosystems was first documented over fifty years ago, shortly after the expansion of industrial plastic production when global manufacturing was below fifty million metric tonnes annually. By 2014, this number had surged to over 300 million metric tonnes per year. Plastic debris of various sizes, from microscopic particles to large fragments, has been detected in all major oceanic regions worldwide. Growing concerns over the impact of plastic waste on marine life have led to further research on the prevalence and consequences of ocean plastic pollution. Marine species such as turtles and fish frequently ingest plastic debris, mistaking it for food, which leads to its accumulation in their bodies. Studies indicate that plastic pollution affects 21% of seabirds and 45% of marine species. Additionally, floating plastic waste can invade new ecosystems, harming commercially and ecologically vital organisms such as corals. It is estimated that approximately 11.1 billion tonnes of plastic waste are deposited on coral reefs in the Asia-Pacific region, a figure projected to rise by 40% by 2025. Plastic waste not only physically damages coral reefs but also introduces foreign pathogens that threaten marine biodiversity. These infections spread to aquatic organisms near contaminated coastal regions, increasing the risk of human exposure through the consumption of seafood such as fish, prawns, and crabs [7].

Historically, plastic waste was often mixed with other refuse and discarded in landfills or inefficient treatment facilities. However, the COVID-19 pandemic has heightened awareness among policymakers about the importance of proper medical plastic waste management due to its environmental and public health risks. Pyrolysis has emerged as a promising method for addressing this issue, offering an efficient way to convert medical plastic waste into drop-in fuel while reducing environmental impact. This study presents a comprehensive analysis of pyrolysis as a solution for medical plastic waste disposal. It explores the characteristics and products of pyrolysis, as well as the challenges associated with this process. By systematically reviewing the pyrolysis of hazardous medical plastic waste, this research provides an environmentally friendly approach to waste management. Furthermore, the physico-chemical properties of fuel derived from pyrolysis have been evaluated against conventional reference fuels, highlighting its potential as an alternative energy source.

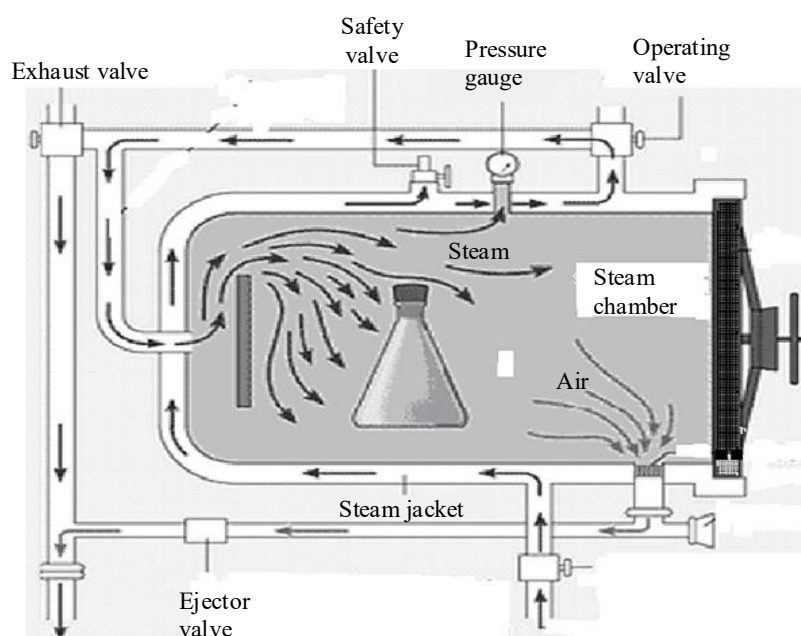
Steam sterilization, commonly known as autoclaving, is a widely used process for disinfecting reusable medical devices. It involves exposing items to high-pressure saturated steam within a sealed chamber to eliminate microorganisms. The steam, applied at elevated temperatures and pressures, irreversibly coagulates and denatures microbial proteins, ensuring sterilization. The complete cycle typically takes between 10 and 60 minutes, depending on the type of material and microbial load. The key parameters in steam sterilization include temperature, pressure, time, and steam quality. This method is highly effective, cost-efficient, and widely used in hospitals and clinical settings for

sterilizing reusable equipment such as metal surgical tools and glassware. While certain plastic materials can withstand multiple sterilization cycles, others degrade after only a few uses, depending on their hydrolytic stability and temperature resistance [8].

Steam sterilization is typically performed at temperatures ranging from 121°C (250°F) to 134°C (273°F), with pressures between 15 and 30 psi (1.0–2.0 bar), and exposure times varying between 10 and 60 minutes. Lower temperatures require longer exposure to achieve complete sterilization. Reusable devices undergo multiple sterilization cycles, and materials used in such devices must retain their structural integrity and functionality after repeated exposure. The process works by using thermal energy from pressurized steam to denature DNA and destroy microbial enzymes.

However, steam sterilization is incompatible with materials that have low melting points or glass transition temperatures near sterilization levels. While metals, glass, and specific polymers such as polycarbonates, silicones, and polyurethanes can withstand the process, some metals may corrode over time. For steam sterilization to be fully effective, the steam must thoroughly penetrate the packaging and directly contact all surfaces of the medical device. This requires porous packaging materials, such as Tyvek® or medical-grade paper, that allow steam to enter while blocking microbial contaminants. Certain design factors, such as air pockets within the device, surface contaminants, and complex geometries with hidden crevices, can hinder the process. These limitations can be mitigated through proper device design, ensuring efficient steam penetration. Additionally, larger and denser devices require longer exposure times to reach the necessary sterilization temperature. However, using materials with high thermal conductivity can help accelerate heat transfer, optimizing the sterilization process.

The image represents the working mechanism of an autoclave, a widely used device for sterilization through moist heat (steam sterilization). The diagram highlights key components such as the steam chamber, exhaust valve, operating valve, ejector valve, steam jacket, safety valve, and pressure gauge. The sterilization process begins when steam is introduced into the chamber, displacing air and increasing pressure. The steam penetrates materials, effectively killing microorganisms, spores, and contaminants [9]. The pressure gauge monitors internal conditions, while the safety valve ensures safe operation. After sterilization, the exhaust valve releases steam, and the chamber returns to normal pressure before items are removed. This autoclave system is essential in medical, laboratory, pharmaceutical, and research settings for effective sterilization (Figure 4).



**Figure 4.** Schematic diagram of an autoclave – steam sterilization process.

Steam sterilization is effective at deactivating all biological organisms, including prions, *Pyronema domesticatum*, and even small viruses. It relies on high temperatures (104–138°C) and moisture, with optimal conditions being saturated steam at elevated pressure. The temperature and duration of exposure are inversely related; lower temperatures require longer times, but some materials are better suited to withstand lower temperatures [10]. This method has been long adopted in healthcare due to its simplicity, cost-effectiveness, and quick operation.

In the 1880s, Koch found dry heat to be less effective than moist heat for sterilization but acknowledged its role in sterilizing certain materials, such as silk threads. Today, steam sterilization is favored for its environmental compatibility, safety, and ability to sterilize even the most resistant biological agents, including prions. However, many plastic materials, chemicals, and metals struggle withstanding steam's high temperature and moisture, as it can cause corrosion and hydration. In hospitals and labs, reusable instruments are primarily sterilized with steam, and the process is also essential for decontaminating infectious waste. There has been renewed interest in this method due to growing environmental concerns, as steam sterilization is non-toxic and effective on most metals, glass, and heat-resistant plastics.

The capacity to tolerate steam sterilization varies based on the chosen temperature. Standard sterilization typically occurs at 121°C (250°F) for 15–20 minutes, while flash sterilization uses temperatures of 134°C (270°F) for 3–4 minutes without wrapping. While effective for many devices, flash sterilization can cause burns if not cooled properly. Longer exposures or lower temperatures (e.g., 240°F or 115°C) may be used, though these are less efficient. For certain materials, steam may be combined with formaldehyde or acids for more effective sterilization at lower temperatures.

## CONCLUSION

While steam sterilization is the go-to method in hospitals, it can damage heat-sensitive medical materials and products, particularly plastics and electronics. Thus, its use in certain applications, like implantable sensor systems, is limited. Autoclaves are a common method of heat sterilization, applying steam at 121–134°C (250–273°F) for a set period, ensuring the inactivation of fungi, bacteria, viruses, and resistant bacterial spores. There are two primary sterilization cycles: gravity-displacement and dynamic air removal. The gravity-displacement method uses steam to push out air, while the dynamic air removal method is more effective by utilizing conditioning air and vacuum cycles to eliminate all residual air from the chamber and the package contents. Flash sterilization, using higher temperatures for a shorter time, is suitable for instruments needing immediate use, like surgical tools. However, this method is not appropriate for implantable sensor systems due to the potential damage from the extreme heat and humidity. Even if the sensors could survive the cycle, it would be difficult to ensure complete sterilization of all internal components.

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