Laser Innovations for Research and Applications

journal homepage: https://lira.journals.ekb.eg/

ISSN: Print 3009-6359 / Online 3009-6472

Microbial water disinfection using Femtosecond laser

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Abstract

Water contamination is a global issue that affects both developed and developing countries. Drinking water should be free of pathogenic microbes to get potable water and for public health preservation in a process called disinfection. The existence of pathogens in water is a significant contributor to numerous human diseases. Microbial water disinfection is crucial for the prevention of outbreaks. Since improved water quality can reduce the incidence of infectious diseases globally by about 4%, according to WHO estimates. Therefore, an efficient water disinfection strategy is desperately needed. This article review discussed microbial water disinfection methods encompassing a range of strategies, spanning from traditional methods, physical techniques (such as ultraviolet radiation), and the chemical techniques (such as chlorine and ozone), to laser based disinfection techniques, femtosecond laser based antimicrobial photoinactivation (aPI), as chemical-free and ecologically conscious alternatives. It is a promising approach that is groundbreaking and efficient without introducing exogenous photosensitizers.

Keywords: Femtosecond Laser light, Antibacterial photoinactivation (aPI), *Enterococcus faecalis.*

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1. Introduction

1. Water contamination

Water has vital importance for all living things (Essamlali, Nhaila et al. 2024). Water contamination is a global issue that affects both developed and developing countries. Water pollution refers to any change in the physical, chemical, or biological characteristics of water that has a negative impact on the health of all living beings (DeZuane 1997). The term "water pollution" refers to the procedure resulting in water being unsafe for consumption due to the introduction of excessive levels of harmful substances (Olaniran 1995). 80% of the global population suffers from severe water pollution (Owa 2013). Different types of pollutants negatively affect water sources such as pathogens, industrial wastes, radioactive wastes, and chemical pollutants such as pesticides and agricultural fertilizers (Chaudhry and Malik 2017, Periolatto, Catania et al. 2020).

Pathogenic bacteria, viruses, and parasites are examples of significant contaminants that cause biological pollution. The feces of both people and animals are the carriers of these contaminants. When they combine with sewage or agricultural runoff water, they are transmitted to the water, resulting in many infectious diseases in humans, like cholera (Pandey, Kass et al. 2014). Sewage water presents a threat to human health when it is released into drinking water (Howard, Charles et al. 2010). It constitutes one of the most dangerous human health challenges in many third-world countries (Bouwer 2000). As a result of the abundance of bacteria, viruses, and parasites in sewage water, it is a major source of spreading diseases (Akpor, Ohiobor et al. 2014).

2. Water pollution's adverse impact on human health

Water pollution and health issues are extremely related (Wang and Yang 2016). Globally, lack of access to clean water and sanitary facilities results in a mortality

rate of 1.6 million yearly of which more than 99% are in developing countries (Organization 2009). Diseases including pneumonia, cancer, diarrhea, mental disorders, and heart disease are among the health threats related to contaminated water (Ullah, Javed et al. 2014). The most significant health risks associated with drinking water in developing countries are caused by pathogens, which are microorganisms causing diseases including bacteria, viruses, and parasites that are transmitted via the oral-fecal pathway (Ashbolt 2004, Gerba 2009). Approximately 2.2 million fatalities worldwide are attributed to water-borne illnesses each year, which also induces a rise in infection instances rate per day. These diseases involve diarrhea, gastrointestinal disorders, and systemic conditions (Organization and Fund 2021). Water-related diseases are contagious diseases induced by pathogens that are most commonly spread by using polluted water while bathing, washing, drinking, cooking, or for other human purposes (Schwarzenbach, Escher et al. 2006). Most water-borne diseases are the result of pathogenic bacteria, per the WHO's drinking water quality guidelines, fourth edition (Cotruvo 2017). For instance, *E. faecalis* poses serious public health risks (Poolman and Anderson 2018). *E. faecalis* can induce serious infections like endocarditis and bacteremia, especially in hospital settings (Ramos, Silva et al. 2020, Krawczyk, Wityk et al. 2021). *E. faecalis* is now one of the three most prevalent pathogens responsible for clinical infections in the aged and people with immune deficiencies, such as urinary system infections, bacteremia, and bacterial endocarditis (Morrison and Wenzel 1986, Murray 2000). Therefore, an efficient water disinfection strategy is desperately needed.

3. Most common water disinfection techniques

Disinfection is a crucial stage in the water treatment procedure to get potable water (Hrudey, Hrudey et al. 2006). It is typically the final stage of the water purification process in which pathogens (bacteria, fungi, parasites, etc.) are eliminated for public health preservation (Huertas, Salgot et al. 2008). Improved water quality can reduce the incidence of infectious diseases globally by about 4%, according to WHO estimates. Therefore, an efficient water disinfection strategy is desperately needed to accomplish this (Schwarzenbach, Egli et al. 2010). The most prevalent conventional techniques in the water sterilization process are the physical techniques (such as ultraviolet radiation) and the

chemical techniques (such as chlorine, and ozone) (Richardson and Postigo 2012).

I. Ultraviolet radiation technique

In developed countries, Ultraviolet (UV) has been the most common technique

in drinking water and wastewater plants for many years (Chatterley and Linden 2010). Emission radiation from UV lamps ranges from 200 to 400 nm (Diffey 2002). UV-B and UV-C radiation (200 to 310 nm) are the most efficient at deactivating bacteria, at 265 nm it reaches its maximum (Nyangaresi, Qin et al. 2018). Because bacteria' DNA and RNA absorb the UV light in this spectrum, it is frequently termed germicidal irradiation (Gray 2014). A UV lamp typically comprises only a fraction of mercury liquid and an inert gas, such as argon (Elliott 2014). When the biological pollutants in water are irradiated with UV radiation, their genetic structure is negatively affected (Bergmann, Iourtchouk et al. 2002, Hijnen, Beerendonk et al. 2006). The bacterial inhibition level depends on the UV radiation exposure time (Hijnen, Beerendonk et al. 2006). The primary drawback of employing UV radiation is the absence of persistent disinfection (Zhang, Li et al. 2020).

To maintain persistent disinfection in the water supply network, chlorine is frequently added after UV sterilization (Wenjun and Wenjun 2009). To ensure that nucleic acid is irreversibly destroyed, a high enough dose of UV radiation is applied (Poepping, Beck et al. 2014). Since the majority of UV lamps consist of quartz tubes containing mercury atoms, the fracture of the lamps poses a potential risk of mercury toxicity (Bakari 2011). As there is some possibility for the human body to be exposed to UV-C light during the disinfection process, it constitutes further hazards because UV-C light has carcinogenic influences on living cells (Sliney and Stuck 2021). Due to the significant attenuation coefficient of UV light in water, the radiation energy drops noticeably as it passes through water (Hale and Querry 1973). The penetration level of UV radiation, whatever pure water, is limited to 10 cm, making it ineffective for treating water resources with high-depth (Schmid, Hoenes et al. 2019).

II. Ozonation technique

For almost a century, ozone has been utilized primarily in Europe as a water disinfectant agent, but its utilization is now growing all over the world (Ellis 1991). Ozone (O_3) is the triatomic state of oxygen that is unstable and significantly reactive (Roshchina, Roshchina et al. 2003). UV irradiation or electric discharge are two ways to generate ozone from oxygen (Oyama 2000). The microbial membrane's organic components become oxidized by ozone causing cell wall damage, and cell lysis. As a result of the microorganism being exposed to the ambient environment, the cell immediately dies (Vikas and Lakshminarayana 2017). Ozone as a treatment method has some drawbacks, including being a major source of air pollution and irritation to the skin, eyes, respiratory system, and mucous membranes (Patocka and Kuca 2014). There's a significant possibility of water recontamination in the water supply network when employing the ozonation technique because the ozone level in water decreases quickly (Khadre, Yousef et al. 2001). The ozonation process is highly costly, particularly operation procedure costs, as it demands high energy consumption and highly qualified experts for production and maintenance systems (Pichel, Vivar et al. 2019). Moreover, organic materials and bromide in water interact with ozone, resulting in carcinogenic byproducts including ketones, aldehydes, and bromate (Manasfi 2021). As pathogens have an elevated level of bicarbonate ions, which suppress the free radical interaction generated during ozone degradation, free radicals are typically less efficient for deactivating microorganisms than molecular ozone (Zuma, Lin et al. 2009). Furthermore, certain bacteria are shielded from ozone by pigments called carotenoids and flavonoids (LeChevallier and Au 2004).

III. Chlorination technique

In several countries, chlorination (Cl) is the most widely employed purification method in water treatment plants (Achour and Chabbi 2014). Using this method, either gaseous chlorine or chlorine derivatives are introduced to the water (Galal-Gorchev 1996). The liquid chlorine can be obtained by the electrolysis technique (Ghernaout and Ghernaout 2010). During the chlorination procedure, chlorine combines with water and produces ions of hypochlorite and hypochlorous acid

(Gordon and Tachiyashiki 1991). They are frequently called free chlorine, that react highly effectively with most constituents of the microbial cell (Ersoy, Dinc et al. 2019). Chlorination may also destroy bacteria by interrupting their metabolism and protein production (Benarde, Snow et al. 1967, Martino 2019) or by altering the sequence of pyrimidine and purine nucleotides, which results in genetic mutations (Hoyano, Bacon et al. 1973). It is an inexpensive and efficient disinfectant agent (Nozaic 2004). Since residual chlorine in water remains for an extended period, its disinfection effect persists throughout water distribution systems and storage tanks (Propato and Uber 2004). The significant drawback of employing chlorine is that when it interacts with naturally occurring substances in the water, it can yield hazardous byproducts, like trihalomethanes and haloacetic acid, which are carcinogenic (Aslani, Hosseini et al. 2019). Consequently, these byproducts need an additional treatment method (Zhai, He et al. 2017). The excessive amount of chlorine causes undesirable taste and smell as well as inflammatory impacts on mucous membranes (Webber, Atherton et al. 2015, Zellner and Eyer 2020). Some kinds of bacteria, such as spore-producing bacteria like Bacillus or Clostridium, once they propagate as spores, become significantly resistant to free chlorine (Luo, Wu et al. 2021).

It has been demonstrated that almost all bacteria that exhibit resistance to chlorine are either Gram-positive or acid-fast, such as Mycobacterium and Nocardia, because Gram-positive bacteria have more intense cell walls than Gram-negative bacteria (Ngwenya, Ncube et al. 2012, Chen, Chen et al. 2023). Traditional disinfection techniques have many drawbacks and cause obstacles to the water treatment processes (Shannon, Bohn et al. 2008). Light-based disinfection techniques are chemical-free and ecologically conscious alternatives (Jo and Tayade 2014). Antimicrobial photoinactivation (aPI) may represent a highly believed alternate solution to other treatment techniques (Niculescu and Grumezescu 2021). Antimicrobial photoinactivation (aPI)'s impressive results in the photoinactivation of many kinds of clinically relevant bacteria could suggest a significant potential for the effective deactivation of pathogens in water (Jemli, Alouini et al. 2002, Costa, Alves et al. 2008).

IV. Antimicrobial photoinactivation (aPI) technique

Antimicrobial photoinactivation (aPI) relies on the dynamic reaction of a photosensitizer at a particular wavelength of radiation and cellular oxygen, which facilitates the selected tissue decomposition (Rocha 2016). aPI has been demonstrated to be effective at destroying pathogens, such as viruses, fungi, and bacteria (Saini, Lee et al. 2016). Antimicrobial photoinactivation (aPI) is known as an antibiotic-free method for deactivating bacteria, particularly antibiotic-resistant pathogens (Taylor, Stapleton et al. 2002, Hamblin and Hasan 2004, Jori and Brown 2004). To initiate a photochemical reaction, three fundamental elements are required: a light-sensitive component existing in the selected tissue called a photosensitizer, a source of radiation with a specific wavelength, and cellular oxygen, which is required for the generation of reactive oxygen species (ROS) (Chalisha, Febrianti et al. 2021).

A. Essential components in aPI

1. Light source

Several light sources, such as lasers, halogen lamps, and light-emitting diodes, have been used for aPI (Yanovsky, Bartenstein et al. 2019). Conventional light sources emit incoherent light with thermal effects that must be averted in aPI. Filters are used to select the wavelength of light suitable for the tissue of interest (Brancaleon and Moseley 2002, Mitton and Ackroyd 2008).

1.1. Laser in aPI

The previously mentioned drawbacks would be avoided and further advantages would be provided by the employment of the laser technique (Zimbelmann, Hermsdorf et al. 2022). Due to lasers' particular characteristics, they are more efficient than other sources of light (Meijer, Du et al. 2002). Laser radiation is characterized by monochromaticity, coherence, directionality, and high intensity (Williams 2008). One of the significant fundamental principles of lasers is monochromaticity, which directly affects tissue and cell activity depending on the properties of the laser beam. This enables an effective match to

the photosensitizer max absorption peak, allowing for ultimate photoactivation and the induction of biological reactions (Conlan, Rapley et al. 1996, Santamato, Solfrizzi et al. 2009). This characteristic affords laser sources to generate thermal effects on the target tissue less than those generated by broadband spectrum sources (Mylona, Anagnostaki et al. 2020). Laser sources provide high-power radiation ranging from hundreds of mW to several W (Stafford, Fuentes et al. 2010). Furthermore, by employing optical fibers, the laser beam is efficiently focused and can be directly delivered to the target tissue even if at a high penetration depth (Issa and Manela-Azulay 2010, Van Straten, Mashayekhi et al. 2017). It has been demonstrated that the laser technique has antimicrobial activity of pathogens and their biofilms (Rupel, Zupin et al. 2019). In aPI systems, pulsed laser sources are preferable to CW laser sources due to their minimal thermal effect (Pick 1997). Pulsed lasers provide several adjustable factors, including exposure time, power density, wavelength, pulse duration, and energy. This enables the selection of the most effective laser characteristics that suppress bacteria (Chavan, Yadav et al. 2023). Antibacterial photoinactivation using femtosecond lasers is one intriguing light option (Yoneyama and Katsumata 2006, Gois, Kurachi et al. 2010), that is being studied nowadays to treat resistant bacteria (Dai, Huang et al. 2009, Wainwright 2009). The significant characteristic of lasers is that their influences are assisted through a mechanism termed "photo biostimulation" instead of heat stimulation (Lin, Josephs et al. 2010).

2. Photosensitizers

They are components susceptible to light, absorb a specific wavelength, and then the energy absorbed is transferred to certain cellular components to damage the cell being targeted. They can be naturally present inside the cell, or exogenously introduced to the cell (Antognazza, Abdel Aziz et al. 2019). There are many recognized photosensitizers, instances of these natural compounds are flavins and porphyrins (Baier, Maisch et al. 2006, Mesquita, Dias et al. 2018). Porphyrins have significant absorption bands in the range of 380–420 nm, while riboflavin and other flavins show absorption spectra in the range of 340–480 nm (Hoenes, Hess et al. 2018). The maximum absorption band of both porphyrins and flavins is approximately 405 nm and 450 nm, respectively.

The corresponding ratio of these two endogenous photosensitizers may affect the bacterial susceptibility to photoinactivation at a specific wavelength (Wang, Ferrer-Espada et al. 2019, Hessling, Wenzel et al. 2020). It has been thought that bacteria's major endogenous photosensitizers are porphyrins (Amos-Tautua, Songca et al. 2019). They are biomolecules crucial for the bacterial heme production process (Dailey, Dailey et al. 2017).Numerous facultative and anaerobic species of bacteria have been shown to possess naturally occurring porphyrins (Soukos, Som et al. 2005, Fyrestam, Bjurshammar et al. 2015, Yang, Wang et al. 2017).

The photoinhibition activity of violet light (400–420 nm) in bacteria is mainly caused by coproporphyrin III, protoporphyrin IX, and uroporphyrin III (Ashkenazi, Malik et al. 2003, Feuerstein, Ginsburg et al. 2005, Maclean, Macgregor et al. 2008, Amin, Bhayana et al. 2016). Aminolaevulinic acid (ALA) is the initial compound in a series of intermediate molecules resulting in porphyrins (Lim, Rideout et al. 1983, Bu, Myers et al. 2003). Although ALA is not classified as a photosensitizer, it is an essential component for heme production (Zhang, Fang et al. 2011, Quehl, Hollender et al. 2016), optimizing cytochrome c oxidase activity to promote the oxidative phosphorylation process (Ogura, Maruyama et al. 2011, Sugiyama, Hagiya et al. 2014). It is also known that flavins, vital for bioenergetic reactions and optimal growth, regulate redox processes in oxygen cellular metabolism (Turner, Huynh et al. 2020). Blue light with antimicrobial characteristics in the 450–470 nm range is thought to be caused by flavins, including riboflavin, which are considered endogenous photosensitizers (Dai, Gupta et al. 2012, Hoenes, Hess et al. 2018, Plavskii, Mikulich et al. 2018).

B. The role of visible light in inactivation of pathogens in photochemical reactions

Over the past fifteen years, visible light has been widely employed in disinfection methods because it is safe for people while still having the ability to inhibit serious microorganisms (Guffey and Wilborn 2006, Maclean, MacGregor et al. 2008). Downes and Blunt were the first to discover the photoinactivation characteristics of visible light in the nineteenth century (Downing and Blunt

1878). Microbial photoinactivation with visible light is a potential antimicrobial technique widely used in applications (MacLean, Booth et al. 2013, Shehatou, Logunov et al. 2019, Hoenes, Spellerberg et al. 2020). It has been demonstrated that visible light in the spectral range from 400 to 470 nm, particularly violet and blue light at 405 and 470 nm, show significant bacterial photoinactivation (Kim, Kim et al. 2013, Tim 2015). The majority of endogenous photosensitizers exhibit absorption bands in the visible light range (Abdelsalam Mohamad 2022). This property facilitates directly stimulating endogenous photosensitizers leading to the destruction of bacteria (Lipovsky, Nitzan et al. 2010). It stimulates the production of significant quantities of reactive oxygen species (ROS), which attack DNA, nuclei, proteins, lipids, mitochondria, and membranes of the target cell (Malik, Hanania et al. 1990). Blue light's antibacterial activity against various bacterial species varied depending on the type and amount of endogenous photosensitizers present in the bacteria, the capacity of the cells to produce antioxidants, and the properties of the light source (wavelength, intensity, exposure time, and power) (Lipovsky, Nitzan et al. 2010, Murdoch, Maclean et al. 2012). Based on the latest studies, blue light may possess bactericidal and bacteriostatic effects directly by bacterial growth suppression or indirectly by disrupting the metabolism of target bacteria leading to ceasing bacterial multiplication and biofilm formation (Feuerstein, Persman et al. 2004, Al-Mamoori, Hussain et al. 2015, Cohen-Berneron, Steinberg et al. 2016, Gomez, Huang et al. 2018, Mohamad, Milward et al. 2021).

C. Antimicrobial Photoinactivation mechanism

The mechanism of inhibition of bacteria isn't based on the thermal effect of radiation (Moritz, Gutknecht et al. 1997). Several studies have investigated photoinactivation mechanisms. The cell membrane has been identified as a significant target among cell components (Kumar, Ghate et al. 2015, McKenzie, Maclean et al. 2016). Nucleic acid damage was frequently detected (Adair and Drum 2016, Kim and Yuk 2017). Nevertheless, no evidence of DNA strand separation was observed (Kumar, Ghate et al. 2015, Kim, Mikš-Krajnik et al. 2016), but genetic mutations were detected (Adair and Drum 2016, Yang, Wang et al. 2017). DNA repair processes may eliminate nucleic acid damage (Imray and MacPhee 1973). This suggests that nucleic acid disruption

might happen, but it is not the primary explanation for bacterial photoinactivation (Valduga, Breda et al. 1999, Hamblin and Hasan 2004, Durantini 2006). For illustration, it has been demonstrated that aPI technique may effectively destroy the Deinococcus radiodurans, which is recognized for having a highly effective DNA-repairing system (Schafer, Schmitz et al. 1998). The commonly recognized explanation of blue light photoinactivation of microorganisms is that visible light excites endogenous photosensitizers like flavins and porphyrins, which induce reactive oxygen species production, resulting in oxidative stress and cell death (Ramakrishnan, Maclean et al. 2016).

For illustration, it has been demonstrated that overall photoinhibition effect within certain bacteria may result from more than one type of endogenous photosensitizer (Hoenes, Bauer et al. 2021). When photosensitizer is exposed to light radiation with a particular wavelength, it is excited from the ground level to a singlet excited level. Afterward, the photosensitizer can either shift to a triplet energy state or emit fluorescence during the deexcitation process to the ground state (Ochsner 2001). Two possible distinct reactions—type I and II—allow the photosensitizer in the triplet state to interact with cellular components (Spikes 1989), as illustrated in Figure 1 (Sai, Lee et al. 2021).

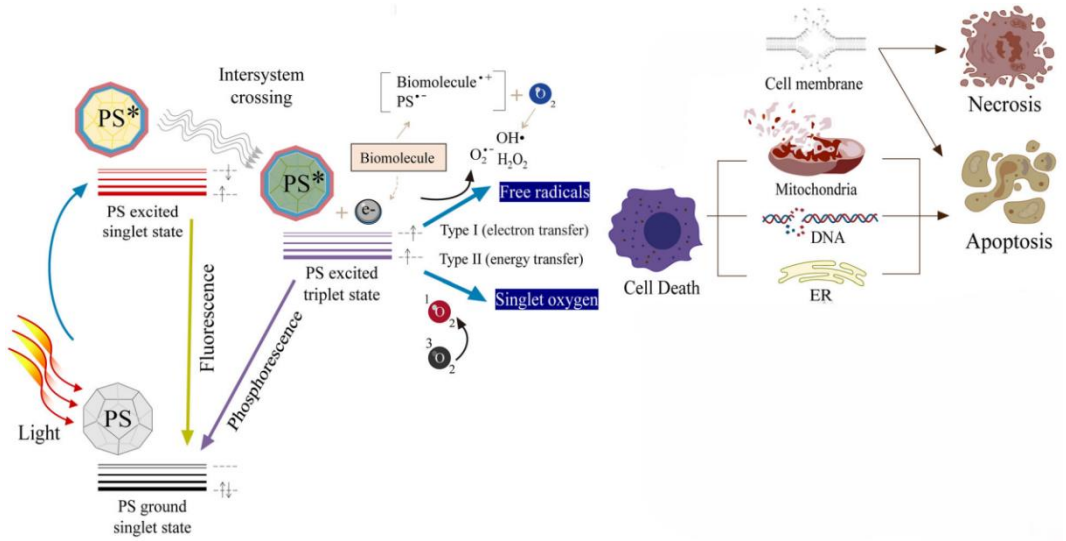

Fig. 1. The diagram shows photodynamic reactions and cellular death mechanisms in the PDT technique. (Sai, Lee et al. 2021)

In the type I pathway, the photosensitizer in the excited energy state undergoes a process known the electron transfer with cellular components. This generates significantly reactive free radicals that react with cellular oxygen molecules generating significantly reactive oxygen species, including superoxide, hydroxyl radicals, and hydrogen peroxide, which may destroy the cell membrane structure and lead to irreversible cellular damage (Sharman, Allen et al. 1999, Takasaki, Aoki et al. 2009). In the type II pathway, the photosensitizer in the triplet state may interact with cellular molecular oxygen via an energy transfer mechanism, generating singlet oxygen ($^1O_2$) that is significantly reactive and can react with various cellular components to stimulate oxidative stress on the entire cell, including the cell membrane (Juzenas and Moan 2006). For aPI, cellular destruction and treatment are achieved by the reactive species generated from type I and type II interactions (Oleinick, Morris et al. 2002). Both type I and type II interactions may take place concurrently, and the photosensitizer and cellular oxygen level control the proportion of these processes to each other (Dolmans, Fukumura et al. 2003, Donnelly, McCarron et al. 2008, Lee, Hsu et al. 2020). Nevertheless, during PDT, type II interaction is prevalent and singlet oxygen is the main lethal factor in charge of cell destruction (Fitzgerald 2017). The quantum rate of singlet oxygen production is estimated based on the quantum yield and lifetime of the photosensitizer's triplet energy state (Adarsh, Shanmugasundaram et al. 2012). Increased irradiance and exposure time stimulate photosensitizers to generate more reactive oxygen species, which raises the rate of bacterial destruction (Jiang, E et al. 2020).

Among the cellular constituents attacked by reactive oxygen species generated during a PDT are proteins, membrane lipids, nucleic acids, carbohydrates, and thiols. Since proteins are the most prevalent substances within cells, they are shown to be the primary target (Rapacka-Zdończyk, Woźniak et al. 2021). The majority of porphyrin compounds generate singlet oxygen, which interacts with sulfur-containing and aromatic amino acids to produce poisonous compounds that may build up in the cell (Michaeli and Feitelson 1994). The peroxidation of lipids triggered by reactive oxygen species damages cell membranes and energy generation and transmission operations (Alves, Santos et al. 2013). Superoxide dismutase, catalase, and peroxidase are examples of antioxidant enzymes that

provide shielding from certain reactive oxygen species. Still, they are ineffective against singlet oxygen, the primary reactive oxygen species in photodynamic activity, as reported in previous studies (Müller-Breitkreutz, Mohr et al. 1995, Wainwright and Crossley 2004, Maclean, Macgregor et al. 2008).

Applications for aPI

The latest study has shown that aPI can be effective in inhibiting pathogens so, it could be employed as a treatment method for bacterial infections (O'Riordan, Akilov et al. 2005). aPI is being investigated as a potential substitute for the treatment of surface, ground, and drinking water as many research findings have demonstrated its efficacy in the destruction of microbes in sewage water (Jemli, Alouini et al. 2002, Bonnett, Krysteva et al. 2006, Carvalho, Gomes et al. 2007). One promising light candidate is femtosecond laser based antimicrobial photoinactivation (aPI) (Yoneyama and Katsumata 2006, Wainwright 2009, Ahmed, El-Gendy et al. 2021, Ahmed, El-Gendy et al. 2021), which is actively being investigated for the treatment of resistant microbes (Dai, Huang et al. 2009, El-Gendy, Nawaf et al. 2022). The photoinactivation of femtosecond laser irradiation, without any prior addition of exogenous photosensitizers, against vancomycin-resistant *Enterococcus faecalis* V583 (VRE) was investigated. The most effective wavelengths were 430 nm and 435 nm at a fluence of 1000 J/cm^2, causing a nearly 2-log reduction (98.6% and 98.3% inhibition, respectively) in viable bacterial counts (El-Gendy, Ezzat et al. 2024). This is the first study to report an optimized wavelength for the inactivation of VRE using visible femtosecond laser light.

Conclusion

The existence of pathogens in water is a significant contributor to numerous human diseases. Microbial disinfection procedure of drinking water is crucial to get potable water and for public health preservation. This article review discussed the prevalent microbial water disinfection techniques. The conventional techniques in the water disinfection process, physical techniques (such as ultraviolet radiation) and chemical techniques (such as chlorine, and ozone), have many drawbacks and cause obstacles to the water treatment

processes. Light-based disinfection techniques are chemical-free and ecologically conscious alternatives. Antimicrobial photoinactivation (aPI) may represent a highly believed alternate solution to other treatment techniques. aPI's impressive previous studies in the photoinactivation of many kinds of clinically relevant bacteria could suggest significant potential for the effective deactivation of pathogens in water. The demand for cutting-edge disinfection methods has rekindled research on photoinactivation with visible light, which may be groundbreaking and efficient without introducing exogenous photosensitizers.

Funding: Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Data availability: Data will be made available on request.

Competing Interest: the authors declare that there are no conflicts of interest related to this article.

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