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WAYS OF IMPROVING THE METHOD OF USING UV RADIATION FOR DISINFECTING DRINKING WATER (LITERATURE REVIEW)

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Introduction. Disinfection of sweat water is one of the main factors of the epidemiological well-being of the population. The classic and most common method of water purification is the use of chemicals. But this method has a whole effect on chemicals, in particular, on chemicals that can cause health problems, in particular, when chlorine compounds are used as a negative disinfecting agent. In addition, during military operations or man-made disasters, there is a need for individual means of water disinfection. This method, an alternative to the classical method, is the use of ultraviolet radiation for water disinfection. Today, during infectious industrial disinfection at city water treatment plants, UV radiation is used in combination with chemical and other physical methods of disinfection of drinking water. But today, low-pressure UV lamps work there, which additionally creates a large amount of ozone. For individual use, even in conditions where the power supply is limited or absent, this is unacceptable. Therefore, in the context of compactness and energy saving, it is effective to use LED lamps, which have an undeniable advantage over old UV lamps, especially low-pressure mercury lamps. In our review of the features of the work of LEDs, in particular, the bactericidal effect at different wavelengths, the time of their effective use. At the same time, one of the main factors affecting the use of UV LEDs is the possibility of creating monochrome sources of ultraviolet radiation and very low energy consumption, which allows you to create a compact device specifically for individual use. Thus, it is possible to obtain a program that will be effective for disinfecting sweat water without the use of chemicals or boiling.

The aim of the research is to analyze literature data and determine ways to improve the method of using UV radiation for drinking water disinfection.

Materials and methods of the research. Analytical review of scientific publications was carried out using scientometric databases SCOPUS, Web of Science, Index Copernicus International Google Scholar CrossRef and others, periodicals and publications.

Results. The advantages and disadvantages of the main methods of drinking water purification are considered and summarized, depending on their effectiveness, convenience, and the presence of side effects for human health. Modern ultraviolet LEDs have been found to be a promising alternative for water disinfection due to many advantages over traditional means and methods. Their use opens up the possibilities of using various wavelengths, opening angles and innovative designs. The unique characteristics of UV LEDs, including multiple wavelengths and pulsed illumination, can increase disinfection efficiency not only under optimal conditions, but also when used in the field, during combat operations, or in emergency situations where the normal water supply is disrupted.

Conclusions. Today, in the conditions of the Russian war against Ukraine, there is an urgent need to develop a portable device for disinfecting drinking water in the field, during hostilities, or in emergency situations (natural disasters, man-made accidents and disasters, etc.), to provide military personnel or civilians population with drinking water without the risk of infectious diseases transmitted by the fecal-oral route. A promising direction of water disinfection may be the development of methods and devices using portable energy-saving sources of UV radiation based on LED technologies.

Key words: ultraviolet radiation, drinking water disinfection, microorganisms, UV lamps, UV LED monochrome source

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Availability of access to clean drinking water has always been one of the cornerstones of protecting a population from infectious diseases. Infections transmitted through water have always been one of the greatest dangers to people's health. Outbreaks of dysentery (bacterial and amoeboid), cholera, rotavirus infection, and other equally dangerous diseases continue to haunt humanity in the 21st century [1]. The key factor in all these troubles is water.

In Ukraine, the problem of clean drinking water, at the moment, is also very relevant in connection with the beginning of the Russian invasion of Ukraine. In a war zone, in the absence of electricity or in the field, the availability of clean drinking water is a key factor. This item is especially very important for the military. So, boiling water is the best procedure for its disinfection. In the conditions of combat operations, when the action group is in the enemy line, it is not always possible to use fire. The using of special chemical tablets for water purification is also an effective tool. However, the effect of the vast majority of these tablets is based on the use of chlorine. Therefore, disinfection is effective, but the water becomes extremely saturated with chemicals.

The method of using special chemical tablets for water disinfection is one of the most common methods of water supply. Chlorine and its derivatives can destroy bacteria and viruses in water, which makes this method effective enough. At the same time, the correct calculation of the chlorine dose is very important to achieve the maximum efficiency of disinfection. Water chlorination also has a number of disadvantages. The risk of the formation of carcinogenic substances is the main disadvantage. In addition, chlorine and its derivatives can affect the functioning of the gastrointestinal tract, liver and cardiovascular system.

Thus, water chlorination is an effective method of water purification, but it has many disadvantages. The choice of water purification method should be based on specific conditions and needs, as well as on the absence of negative consequences for human health and the environment.

The use of ultraviolet radiation is a good alternative to the water purification methods listed above. Now UV radiation is widely used as a disinfection method for cleaning drinking water. This method became very popular in the 1990s when it was found that water containing *Cryptosporidium parvum* and *Giardia lamblia* could be disinfected using UV radiation [2]. These are simpler organisms that cause cryptosporidiosis and giardiasis. As we noted above, unlike other disinfection methods such as chlorination or ozonation, UV irradiation does not require the addition of chemicals and produces a negligible amount of disinfection by-products [3]. Different bacteria have different sensitivity to ultraviolet radiation. For example: a $4 - \log_{10}$ reduction of an isolate of *Mycobacterium avium* grown in the environment requires a dose of 128 J/m^2 at a wavelength of 254 nm [4], while the same reduction of an isolate of *Escherichia coli* requires a dose of 81 J/m^2 [5]. In addition, the effectiveness of UV radiation, and the dose required for disinfection is affected by the suspended particles contained in the water. They can absorb and scatter ultraviolet light. Therefore, a mandatory condition for the use of UV radiation for water disinfection is its preliminary filtration from foreign impurities [6, 7]. An additional factor the advantage of UV irradiation over chemical agents is the lack of resistance of bacteria to ultraviolet [8].

In 2000, systems of UV irradiation of water for the purpose of disinfection began their active development. In particular, they started to be actively used at large urban purification stations

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[9]. Small household UV disinfection systems have also become available [10]. The main sources of ultraviolet radiation for water disinfection systems are mercury lamps of low or medium pressure [11]. However, the use of lamps of this type raises many questions and concerns. First, such lamps are fragile and contain toxic mercury, which is dangerous for the environment and requires appropriate disposal [12]. In addition, these lamps are energy-consuming, with low efficiency. And they have a short service life, approximately 10,000 hours [13, 14].

Recently, the development and improvement of modern technologies, monochrome sources of UV radiation based on light-emitting diodes (LEDs) are a good alternative to the use of mercury lamps. In terms of their power and functionality, they occupy an intermediate position between bactericidal lamps and sources of preventive UV radiation. A light-emitting diode (LED) is a semiconductor device that emits light in a narrow spectrum produced by electroluminescence. The wavelength of the radiation depends on the semiconductor materials. Commercial visible light-emitting diodes have been available for almost 50 years and have a variety of applications, especially in the lighting industry, due to their increasingly high efficiency and low cost [15].

Conventional UV lamps, such as mercury lamps, operate at high voltage. Currently, due to the high demand for energy and the toxicity of mercury, other sources of UV radiation are of greater interest.

AlGaN and AlN crystals are materials for shortwave (200–280 nm) UV LEDs. These LEDs do not contain toxic substances (such as mercury) and use less energy than traditional UV sources, because LEDs transfer more energy to light and use less energy as heat. In addition, UV LEDs are difficult to break, emitting only the required wavelength (eg 260 nm). The use of UV LEDs for water purification is a fairly new method, as UV LEDs with fairly short wavelengths have only recently become available. LEDs that emit radiation with wavelengths even up to 210 nm have been developed [16].

Biological effects of different length waves in LED UV emitters

The bactericidal efficiency of UV radiation strongly depends on its wavelength and dose. At the same time, the sensitivity of microorganisms does not necessarily correspond to the absorption spectrum of DNA [17, 18]. Thus, the wavelength of UV radiation is an important factor for disinfection. However, its effectiveness may differ depending on the type of microorganism [19, 20]. Different wavelengths in the range of 315–400 nm (UVA), 280–315 nm (UVB) and < 280 nm (UVC) are used to inactivate microorganisms with UV LEDs. Table 1 shows data on the effect of different wavelengths on the effectiveness of bactericidal action; data taken from published sources [21].

The bactericidal action protocol for UV mercury lamps has been long ago developed and standardized, all the obtained results can be easily compared [33, 34]. At the same time, these protocols should not be used to evaluate ultraviolet LED emitters, because they have significant differences from mercury lamps. In particular, the output power of UVC-LEDs is currently only a few Watts, which is much less than that of low-pressure mercury UV lamps (typically 40 Watts) or high power medium pressure mercury lamps (up to 30 kW).

As a result, UV LEDs must be located directly next to or in the water where disinfection is to occur. It is important to consider that one LED is a point source and creates radiation in the form of a

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Table 1

Summary data on the bactericidal effect of different wavelengths of UV LEDs

Wave le length, nm	Microorganism	Disinfection medium	Dose UV, mJ/cm^2	Log$_{10}$ inactivation	Dose response, mJ/cm^2 per log$_{10}$ inactivation	Sources
250	*B. subtilis*	water	59.2	3	19.7	[22]
254	*Mesophilic bacteria*	water	0.73	0.8	1.0	[23]
255	φX174	water	6.4	3.7	1.7	[24]
255	Qβ	water	30	2.4	12.5	[24]
255	MS2	water	41	3.2	12.8	[24]
255	MS2	water	60	2.3	26.1	[25]
255	T7	water	20	3.9	5.1	[25]
255	*E. coli*	water	9	2.7	3.3	[25]
265	*E. coli*	water	20	3.4	5.9	[26]
265	*E. coli*	water	10.8	4	2.7	[27]
265	*Pseudomonas aeruginosa*	biofilm *in vitro*	7.8	4	2.0	[28]
269	*B. subtilis*	water	40	5.9	6.8	[29]
275	MS2	water	60	2.1	28.6	[25]
275	T7	water	20	4.7	4.3	[25]
275	*E. coli*	water	9	3.8	2.4	[25]
280	*E. coli*	water	13.8	4	3.5	[27]
280	*Mesophilic bacteria*	water	1.37	1.4	1.0	[23]
280	φX174	water	8.9	3.2	2.8	[24]
280	Qβ	water	43	1.5	28.7	[24]
280	MS2	water	58	1.9	30.5	[24]
282	*B. subtilis*	water	60	7.2	8.3	[29]
310	*E. coli*	water	56.9	0.6	94.8	[27]
365	*E. coli*	water	315 000	5.7	55.263	[30]
365	*E. coli*	water	54 000	3.9	13.846	[31]
365	*E. coli*	water /TiO_2	688	3	229	[32]
365	*Mesophilic bacteria*	water	4.22	0.3	12.5	[23]
405	*Mesophilic bacteria*	water	25.58	0.3	88.0	[23]
254/365	*Mesophilic bacteria*	water	4.95	2.4	2.1	[23]
280/365	*Mesophilic bacteria*	water	5.59	3.5	1.6	[23]
254/405	*Mesophilic bacteria*	water	26.31	2.2	11.9	[23]
280/405	*Mesophilic bacteria*	water	26.95	3.5	7.7	[23]

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hemisphere. As a result, there is no uniform irradiation on the surface of the water sample, which leads to complications in the accurate determination of the ultraviolet dose. In addition, the power of UV LEDs can be significantly affected by the operating parameters of currents and voltages, as well as the temperature during operation. Therefore, there is a need to develop a standardized protocol for studying the bactericidal effect of ultraviolet LED emitters, especially for the accurate determination of the ultraviolet radiation dose and the proper operation of the system.

In addition, studies on the bactericidal effect of the combination of UVA and UVC LED emitters are interesting. Some researchers, as can be seen from Table 1, show greater effectiveness of such combinations, others, on the contrary, do not confirm synergistic action. Moreover, they found that the combined wavelengths were less effective than each wavelength applied separately, which could be a consequence of different test microorganisms and wavelength combinations, as well as inefficient thermal management of the experimental setup [26, 27]. These studies show that the combination of certain wavelengths can be a serious way to improve the disinfection efficiency of UV LEDs.

The ability to turn on and off with a high frequency is another unique feature of UV LEDs, allowing pulsed UV light to be controlled. This feature makes UV LEDs desirable for potentially increasing the inactivation efficiency by pulsed irradiation. There are data on enhancing the bactericidal effects of pulsed UV-LED irradiation by using UVA-LED light at 365 nm for the inactivation of Candida albicans and *E. coli* biofilms [35]. They found that pulsed irradiation had significantly greater bactericidal capacity than continuous irradiation with a maximum frequency of 100 Hz and 75 % duty time (percentage of exposure time to total duty time) for the same UV dose. The use of pulsed UV light using UV243 LEDs at 272 nm wavelength to disinfect *E. coli* on agar plates has been shown to be more effective than continuous light. The log of inactivation for pulsed UV radiation at 272 nm with the frequency of 1 Hz and 10 % duty factor was 3.8 times higher than for continuous irradiation based on the same UV dose, indicating a high efficiency of pulsed UV radiation [36].

Time needed for disinfection

Table 2 shows the data of various researchers on the time of inactivation of microorganisms using UV LEDs. The time of exposure to ultraviolet radiation was from 30 seconds to 2 hours [21].

Today, the main methods of water disinfection using UV radiation are external irradiation of water in tanks/pools or irradiation of water in special tanks that are inserted into the supply system and where several lamps are located directly immersed in the water. Figure shows an illustrative diagram of such a system.

Accordingly, research on water disinfection using ultraviolet LEDs is very relevant. UV LEDs are a promising alternative to traditional UV mercury lamps [44], but more research is needed to better understand the application of UV LEDs for water disinfection. In addition, some unique features of UV LEDs, such as wavelength diversity and pulsed illumination, must be studied and understood, as well as their effect on the inactivation of microorganisms.

Given that UV LEDs are compact and emission parameters such as emission wavelength, opening angle, and radiation distribution can be tuned, they can increase the variety of design solutions to optimize radiation flow and its distribution, as well as source geometry and process kinetics [45].

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Table 2

Data on the time required for water disinfection using UV LEDs

Wave le length, nm	Microorganism	Disinfection medium	Duration of exposure	Log_{10} inactivation	Sources
254	*E. coli*	water	30 s	3.5	[37]
260	*E. coli*	water	50 min	2.5	[38]
269	*E. coli*	water	5 min	3–4	[20]
276	*E. coli*	water	5 min	3–4	[20]
280	*E. coli*	water	30 s	7	[37]
365	*E. coli*	water	30 s	2.7	[37]
365 (impulse)	*E. coli*	biofilm	1 min	3	[39]
365 (impulse)	*Candida albicans*	biofilm	1 min	3	[39]
365	*Vibrio parahaemolyticus*	water	6 min	1	[40]
375	*E. coli*	biofilm	2 hr	2	[41]
375	*Streptococcus mutans*	water	15 min	4	[42]
405	*E. coli*	water	30 s	3.3	[37]
254/365	*E. coli*	water	30 s	7	[37]
280/365	*E. coli*	water	30 s	7	[37]
280/405	*E. coli*	water	30 s	7	[37]

Thus, it is possible to summarize the advantages and disadvantages of the various main methods of drinking water disinfection (Table 3).

Thus, the main methods of decontamination of drinking water using physical factors and chlorination have both certain advantages and disadvantages, which is the basis for their use in certain conditions. But still, the use of LED sources of UV radiation looks quite attractive from the point of view of mobility and convenience of technology, absence of secondary water pollution, and energy saving.

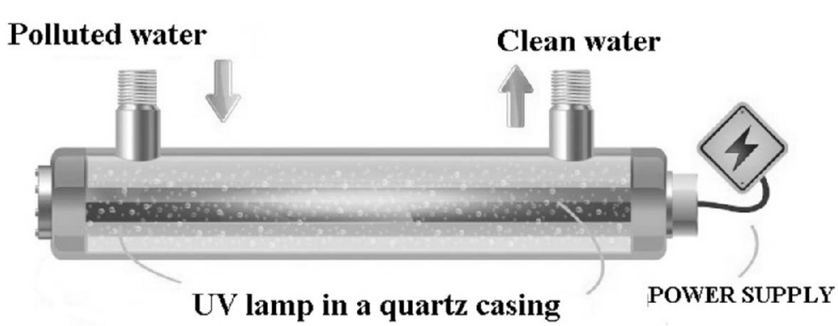

Figure. Ultraviolet filter for water [43]

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Table 3

Advantages and disadvantages of basic methods of drinking water disinfection

Basic methods of water disinfection		**Advantages**	**Disadvantages**
Chemical	Chlorination	High efficiency of chlorine in relation to 99 % of microorganisms; long after-effect	The need for accurate dosing; high toxicity of the main reagent and its derivatives
	Ozonization	High efficiency in relation to microorganisms; absence of secondary interaction products; removes foreign tastes and odors	Requires expensive equipment; increased requirements for safety equipment and personnel training; the impact of ozone on the body is generally toxic, irritating, carcinogenic and mutagenic, and can also lead to premature death
	Complex organic compounds use	High efficiency against microorganisms, in particular – destruction of biofilms; absence of unpleasant odors; convenient form for transportation and storage	The need for accurate dosing; insufficiently studied impact on the human body; the need to remove excess reagent from drinking water
Physical	Boiling	Ease of performance; no need for additional equipment; effective against most pathogenic microorganisms; in addition to disinfection, the level of hardness and turbidity decreases	Significant increase in energy consumption with an increase in the volume of water; long duration; the possibility of secondary pollution; the need for a heat/fire source
	UV treatment	LED lamps	The method is easy to use; does not require bulky equipment; there is no need for constant dosing of reagents; does not introduce secondary pollution into the water, unlike disinfection with reagents; low energy consumption; compactness
		Mercury lamps	The method is easy to use; there is no need for constant dosing of reagents; does not introduce secondary pollution into the water, unlike disinfection with reagents

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Conclusions

1. Modern and energy-saving UV LEDs are a promising alternative for water disinfection due to many advantages over traditional mercury lamps of low pressure. This opens up the possibilities of using various wavelengths, opening angles and innovative designs.
2. The unique characteristics of UV LEDs, including multiple wavelengths and pulsed illumination, can significantly increase inactivation efficiency beyond optimal conditions. However, for a more effective use of UV LEDs, it is necessary to further investigate the factors and mechanisms of their influence on microorganisms. The features of UV LEDs as point sources of UV radiation with an adjustable directional pattern provide great flexibility for new designs.
3. The design of new UV LED sources for water disinfection must consider three points: media hydrodynamics, radiation distribution, and kinetics of processes. Each of these phenomena can be realized with a greater degree of freedom, due to the use of UV LEDs as a source of radiation compared to UV mercury lamps.

References

1. Hart R. Cholera Making An «Unwelcome Comeback», WHO Warns. Here's What You Need To Know About One Of Humanity's Most Feared Killers. Forbes [Internet]. 2022 Oct 6 [cited 2023 May 25]. Available from: https://www.forbes.com/sites/roberthart/2022/10/06/cholera-making-an-unwelcome-comeback-who-warns-heres-what-you-need-to-know-about-one-of-humanitys-most-feared-killers/?sh=38dfa58b6f68.

2. Hijnen WAM, Beerendonk EF, Medema GJ. Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: a review. Water Res. 2006;40:3–22. DOI: https://doi.org/10.1016/j.watres. 2005.10.030.

3. Reckhow DA, Linden KG, Kim J, Shemer H, Makdissy G. Effect of UV treatment on DBP formation. J. Am. Water Works Assoc. 2010;102:100–13. DOI: https://doi.org/10.1002/j.1551-8833.2010.tb10134.x.

4. Hayes SL, Sivaganesan M, White KM, Pfaller SL. Assessing the effectiveness of low-pressure ultraviolet light for inactivating *Mycobacterium avium* complex (MAC) micro-organisms. Lett. Appl. Microbiol. 2008;47:386–92. DOI: https://doi.org/10.1111/j.1472-765X.2008.02442.x.

5. Sommer R, Lhotsky M, Haider T, Cabaj A. UV inactivation, liquid-holding recovery, and photoreactivation of *Escherichia coli* O157 and other pathogenic *Escherichia coli* strains in water. J. Food Protect. 2000;63:1015–20. DOI: https://doi.org/10.4315/0362-028X-63.8.1015.

6. Christensen J, Linden KG. How particles affect UV light in the UV disinfection of unfiltered drinking water. J. Am. Water Works Assoc. 2003;95:179–89. DOI: https://doi.org/10.1002/j.1551-8833.2003.tb10344.x.

7. Farrell C, et al. Turbidity composition and the relationship with microbial attachment and UV inactivation efficacy. Sci. Total Environ. 2018;624:638–47. DOI: https://doi.org/10.1016/j.scitotenv.2017. 12.173.

8. Hamamoto A, Mori M, Takahashi A, Nakano M, Wakikawa N, Akutagawa M, Ikehara T, Nakaya Y, Kinouchi Y. New water disinfection system using UVA light-emitting diodes. Journal of Applied Microbiology. 2007; 103(6):2291–8. DOI: https://doi.org/10.1111/ j.1365-2672.207.03464.x.

9. Muller J, Lem W. UV Disinfection of Storm Water Overflows and Low uvt UVT Wastewaters. IUVA News. 2011;13(3):13–7. Available from: https://iuva.org/resources/Documents/2011/iuva_vol13_issue3-oct_2011_0_0.pdf.

10. Brownell SA, Chakrabarti AR, Kaser FM, Nelson KL. Assessment of a low-cost, point-of-use, ultraviolet water disinfection technology. Journal of Water and Health. 2008;6(1):53–65.DOI: https://doi.org/10.2166/wh.2007.015.

11. Chevremont A-C, Farnet A-M, Coulomb B, Boudenne J-L. Effect of coupled UV-A and UV-C LEDs on both microbiological and chemical pollution of urban wastewaters. Science of The Total Environment. 2012;426:304–10. DOI: https://doi.org/10.1016/j.scitotenv.2012.03.043

12. Close J, Ip J, Lam KH. Water recycling with PV-powered UV-LED disinfection. Renewable Energy. 2006;31(11):1657–64. DOI: https://doi.org/10.1016/j.renene.2005.08.034.

13. Autin O, Romelot C, Rust L, Hart J, Jarvis P, MacAdam J, Parsons SA, Jefferson B. Evaluation of a UV-light emitting diodes unit for the removal of micropollutants in water for low energy advanced oxidation processes. Chemosphere. 2013;92(6):745–51. DOI: https://doi.org/10.1016/j.chemosphere.2013. 04.028.

ISSN 2223-6775 (Print), 2663-9734 (Online), 2786-7897 (Online), Ukrainian Journal of Occupational Health, 2023, 19 (2), 151–160

14. Chatterley C, Linden K. Demonstration and evaluation of germicidal UV-LEDs for point-of-use water disinfection. J Water Health. 2010;8(3):479–86. DOI: https://doi.org/10.2166/wh.2010.124.

15. Ibrahim MAS, MacAdam J, Autin O. Evaluating the impact of LED bulb development on the economic viability of ultraviolet technology for disinfection. 2014;35(4):400–6. DOI: https://doi.org/10.1080/09593330.2013.829858.

16. Taniyasu Y, Kasu M, Makimoto T. An aluminium nitride light-emitting diode with a wavelength of 210 nanometres. Nature. 2006;441:325–8. DOI: https://doi.org/10.1038/nature04760.

17. Chen RZ, Craik SA, Bolton JR,. Comparison of the action spectra 547 and relative DNA absorbance spectra of microorganisms: information important for the determination of germicidal fluence (UV dose) in an ultraviolet disinfection of water. Water Res. 2009;43(20):5087–96. DOI: https://doi.org/10.1016/j.watres.2009.08.032.

18. Mamane-Gravetz H, Linden KG, Cabaj A, Sommer R. Spectral sensitivity of Bacillus subtilis spores and MS2 coliphage for validation testing of ultraviolet reactors for water disinfection. Environ. Sci. Technol. 2005;39(20):7845–52. DOI: https://doi.org/10.1021/es048446t.

19. Linden KG, Shin G, Sobsey MD. Comparative effectiveness of UV wavelengths for the inactivation of Cryptosporidium parvum oocysts in water. Water Sci. Technol. 2001;43(12):171–4. DOI: https://doi.org/10.2166/wst.2001.0731.

20. Vilhunen S, Sarkka H, Sillanpaa M. Ultraviolet light-emitting diodes in water disinfection. Environ. Sci. Pollut. Res. 2009;16(4):439–42. DOI: https://doi.org/10.1007/s11356-009-0103-y.

21. Song K, Mohseni M, Taghipour F. Application of ultraviolet lightemitting diodes (UV-LEDs) for water disinfection: A review, Water Research. 2016;94:341–9. DOI: https://doi.org/10.1016/j.watres.2016.03.003

22. Morris JP. Disinfection of Bacillus subtilis spores using ultraviolet light emitting diodes. Master's thesis, Ohio University; 2012. Available from: http://rave.ohiolink.edu/etdc/view?acc_num=ohiou1338575832.

23. Chevremont AC, Farnet AM, Coulomb B, Boudenne JL. Effect of coupled UV-A and UV-C LEDs on both microbiological and chemical pollution of urban wastewaters. Science of the Total Environment. 2012;426:304–10. DOI: https://doi.org/10.1016/j.scitotenv.2012.03.043.

24. Aoyagi Y, Takeuchi M, Yoshida K, Kurouchi M, Yasui N, Kamiko N, Araki T, Nanishi Y.. Inactivation of bacterial viruses in water using deep ultraviolet semiconductor light-emitting diode. J. Environ. Eng.-ASCE. 2011;137(12):1215–8. DOI: https://doi.org/10.1061/(ASCE)EE.1943-7870.0000442.

25. Bowker C, Sain A, Shatalov M, Ducoste J. Microbial UV fluence-response assessment using a novel UV-LED collimated beam system. Water Res. 2011;45(5);2011–9. DOI: https://doi.org/10.1016/j.watres.2010.12.005.

26. Chatterley C, Linden K. Demonstration and evaluation of germicidal UV-LEDs for point-of-use water disinfection. J. Water Health. 2010;8(3):479-86. DOI: https://doi.org/10.2166/wh.2010.124.

27. Oguma K, Kita R, Sakai H, Murakami M, Takizawa S. Application of UV light emitting diodes to batch and flow-through water disinfection systems. Desalination. 2013;328:24–30. DOI: https://doi.org/10.1016/j.desal.2013.08.014.

28. Bak J, Ladefoged SD, Tvede M, Begovic T, Gregersen A. Disinfection of Pseudomonas aeruginosa biofilm contaminated tube lumens with ultraviolet C light emitting diodes. Biofouling. 2010;26(1):31–8. DOI: https://doi.org/10.1080/08927010903191353.

29. Wurtele MA, Kolbe T, Lipsz M, Kulberg A, Weyers M, Kneissl M, Jekel M. Application of GaN-based ultraviolet-C light emitting diodes – UV LEDs – for water disinfection. Water Res. 2011;45(3):1481–9. DOI: https://doi.org/10.1016/j.watres.2010.11.015.

30. Hamamoto A, Mori M, Takahashi A, Nakano M, Wakikawa N, Akutagawa M, Ikehara T, Nakaya Y, Kinouchi Y. New water disinfection system using UVA lightemitting diodes. J. Appl. Microbiol. 2007;103(6):2291–8. DOI: https://doi.org/10.1111/j.1365-2672.2007.03464.x.

31. Mori M, Hamamoto A, Takahashi A, Nakano M, Wakikawa N, Tachibana S, Ikehara T, Nakaya Y, Akutagawa M, Kinouchi Y. Development of a new water sterilization device with a 365 nm UV-LED. Med. Biol. Eng. Comput. 2007;45(12):1237–41. DOI: https://doi.org/10.1007/s11517-007-0263-1.

32. Xiong P, Hu JY. Inactivation/reactivation of antibiotic-resistant bacteria 706 by a novel UVA/LED/TiO_2 system. Water Res. 2013;47(13):4547–55. DOI: https://doi.org/10.1016/j.watres.2013.04.056.

33. Bolton JR, Linden KG. Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. J. Environ. Eng.-ASCE. 2003;129(3):209–15. DOI: https://doi.org/10.1061/(ASCE)0733-9372(2003)129:3(209).

34. Kuo J, Chen CL, Nellor M.. Standardized collimated beam testing protocol for water/wastewa-

ISSN 2223-6775 (Print), 2663-9734 (Online), 2786-7897 (Online), Ukrainian Journal of Occupational Health, 2023, 19 (2), 151–160

ter ultraviolet disinfection. J. Environ. Eng.-ASCE. 2003;129(8):774–9. DOI: https://doi.org/10.1061/(ASCE)0733-9372(2003)129:8(774).

35. Li J, Hirota K, Yumoto H, Matsuo T, Miyake Y, Ichikawa T. Enhanced germicidal effects of pulsed UV-LED irradiation on biofilms. J. Appl. Microbiol. 2010;109(6);2183–90. DOI: https://doi.org/10.1111/j.1365-2672.2010.04850.x.

36. Wengraitis S, McCubbin P, Wade MM, Biggs TD, Hall S, Williams LI, Zulich AW. Pulsed UV-C disinfection of *Escherichia coli* with light-emitting diodes, emitted at various repetition rates and duty cycles. Photochem. Photobiol. 2013;89(1):127–31. DOI: https://doi.org/ 10.1111/ j.1751-1097.2012.01203.x.

37. Chevremont AC, Farnet AM, Sergent M, Coulomb B, Boudenne JL. Multivariate optimization of fecal bioindicator inactivation by coupling UV-A and UV-C LEDs. Desalination. 2012;285:219–25. DOI: https://doi.org/10.1016/j.desal.2011.10.006.

38. Nelson KY, McMartin DW, Yost CK, Runtz KJ, Ono T. Point-of-use water disinfection using UV light-emitting diodes to reduce bacterial contamination. Environ. Sci. Pollut. Res. 2013;20(8):5441–8. Doi: https://doi.org/10.1007/s11356-013-1564-6.

39. Li J, Hirota K, Yumoto H, Matsuo T, Miyake Y, Ichikawa T. Enhanced germicidal effects of pulsed UV-LED irradiation on biofilms. J. Appl. Microbiol. 2010;109(6):2183–90. DOI: https://doi.org/10.1111/j.1365-2672.2010.04850.x.

40. Nakahashi M, Mawatari K, Hirata A, Maetani M, Shimohata T, Uebanso T, Hamada Y, Akutagawa M, Kinouchi Y, Takahashi A. Simultaneous irradiation with different wavelengths of ultraviolet light has synergistic bactericidal effect on Vibrio parahaemolyticus. Photochem. Photobiol. 2014;90(6):1397–403. DOI: https://doi.org/10.1111/php.12309.

41. Hwang KS, Jeon YS, Choi TI, Hwangbo S. Combination of light emitting diode at 375 nm and photo-reactive TiO_2 layer prepared by electrostatic spraying for sterilization. J. Electr. Eng. Technol. 2013;8(5):1169–74. DOI: https://doi.org/ 10.5370/JEET.2013.8.5.1169.

42. Kim BH, Kim D, Cho DL, Lim SH, Yoo SY, Kook JK, Cho YI. Ohk SH, Ko YM. Sterilization effects of a TiO_2 photocatalytic film against a Streptococcus mutans culture. Biotechnol. Bioprocess Eng. 2007;12(2): 136–9. DOI: https://doi.org/10.1007/BF03028639.

43. [How to choose a high-quality ultraviolet filter] Vencon [Internet] [cited 2023 May 25]. Available from: https://vencon.ua/ua/articles/kak-vybrat-ultrafioletovyj-filtr-dlya-vody. Ukrainian.

44. Muramoto Y, Kimura M, Nouda S. Development and future of ultraviolet light emitting diodes: UV-LED will replace the UV lamp. Semicond. Sci. Tech. 2014;29(8):084004. DOI: https://doi.org/10.1088/0268-1242/29/8/084004.

45. Taghipour F. Is UV-LED the future of ultraviolet water purification? IUVA News. 2013;15(4): 23–6.

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