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WATER DISINFECTION USING ULTRAVIOLET-A AND VISIBLE LIGHT-EMITTING DIODES

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ABSTRACT

A bench-scale disinfection apparatus has been prepared to evaluate the performance of Light-Emitting Diodes (LEDs) on bacterial inactivation. Three sets of Light-Emitting Diodes arrays were used to apply light on water samples. They were; ultraviolet-A LEDs, Blue LEDs, and White LEDs. Each LED array consists of nine LED bulbs. The inactivation of faecal coliforms present in the water sample by the application of LED light treatment was analyzed. It has been observed a 3.70 log reduction of faecal coliforms after 4 hours of ultraviolet-A LED treatment for 0.75 cm water sample depth. Similarly for white LED treatment 2.92 log reduction and for blue LED treatment 2.77 log reduction were observed. Irradiation dosage applied to water sample within 4 hours by ultraviolet-A, white, and blue LEDs were 1252 mJ/cm^2, 10224 mJ/cm^2, and 5040 mJ/cm^2 respectively. To conclude, this study showed that ultraviolet-A, White, and Blue LEDs can inactivate faecal coliforms.

Keywords: Disinfection, Light-emitting diodes, Ultraviolet-A

I. INTRODUCTION

Contaminated drinking water can cause a major health threat to human beings globally. The problem is particularly significant in developing countries and in arid areas where water sources are scarce. In developing countries, surface waters such as rivers, streams and lakes are used for multiple activities, including livestock watering, bathing, and cooking. Defecation and urination often occur near water sources as well. This water, which may be contaminated with pathogenic organisms, is also used for drinking water. People in developing countries may have no other options for drinking water because there is a lack of water distribution infrastructure and lack of funding for developing water treatment systems. Hence implementation of point-of-use (POU) disinfection technologies have higher urge.Most popular method of drinking water treatment at POU level is ultraviolet (UV) light treatment [1].

The portion of the electromagnetic spectrum in which UV radiation occurs is between 100 and 400 nm, as shown in Fig. 1. The UV radiation range is characterized further according to wavelength as long wave (UV-A), also known as near-ultraviolet radiation, middle-wave (UV-B), and short-wave (UV-C), also known as far UV. UV-A radiation occurs between wavelengths of 315-400 nm. UV-B radiation occurs between wavelengths of 280-315 nm. UV-C radiation occurs between wavelengths of 100-280 nm [2].

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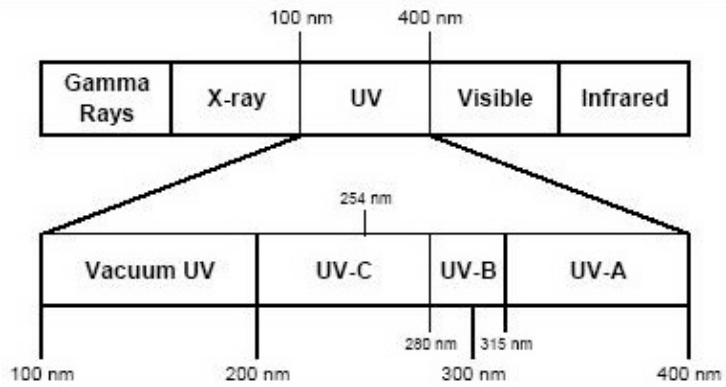

Figure 1 Ultraviolet spectrum

More than five decades the part of electromagnetic spectrum, comprising of UV light in the shorter range (especially 254 nm), is only considered as good disinfectant [3].Now a day's disinfection ability of UV-A radiation is a new area of research interest. In every field of science and technology, change towards sustainability or green technology is happening. In conventional UV disinfection units mercury vapor lamps are being used. Replacing it with less dangerous LEDs will be a good alternative. Moreover, high exposures to UV-C light have harmful effects on humans. So a detailed study of bactericidal effects of UV-A light using LEDs will be useful for sustainable development of water purification.

1.1 Light-emitting diodes

LED is a semiconductor that emits visible light when an electric current passes through it. LEDs can emit light within a very narrow wavelength spectrum and can be considered as a monochromatic wavelength. This is an advantage over traditional visible light sources which are not able to produce monochromatic wavelengths. LEDs have advantages like low energy consumption and high durability. The size of a LED can be made very small and can be easily implemented into existing systems without requiring any special disposal technique at the end of its use. Now, LED has been widely applied to optics, electronics and medicine[4]. Now a day's LEDs can produce UV-A spectrum also. The emitting wavelength of a LED is dependent on the bandgap energy of semiconductor material used for that LED. For an emission at 265 nm bandgap energy of 4.68 eV is required.Such a semiconductor with bandgap energy of 4.68 eV is costly. Most commercially available Indium Gallium Nitride (InGaN) alloys can produce UV-A spectrum (wavelength > 360 nm), with higher external quantum efficiency [5].

1.2 Disinfection using LEDs

Newer trend is the application of light-emitting diodes for generating UV lights. Highly efficient semiconductor-based ultraviolet light emitting diodes could revolutionize UV water purification and lead to completely new solutions that cannot be realized with conventional mercury lamps. Also the application of UV-A and visible spectrum in disinfection technology are a curious path in researches.

Although UV is effective at retarding bacterial growth, it can be harmful to normal cells. UV-B radiations are also responsible for a variety of skin disorders, including cancer [6]. A safe, non-UV-C, light based

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decontamination technology termed high-intensity narrow-spectrum (HINS) light has been recently described. HINS light of 405nm stimulates endogenous microbial porphyrin molecules to produce oxidizing reactive oxygen species (ROS), predominantly singlet oxygen that damages cells leading to microbial death. Specifically 405nm light has been shown to be capable of inactivating a range of predominantly nosocomial pathogens and also Gram negative food-related pathogens. Visible light is used clinically in the treatment of dermatitis, Alzheimer's disease, and muscle analgesia, and is effective at removing bacterial biofilms. Visible light phototherapy seems to be a promising alternative approach to eradicating bacteria with blue light [7].

Lui et al. (2014) concludes that current disinfection technologies are inapplicable in rural and remote regions of developing regions. Populations in rural and remote developing regions will be unable to access centralised piped potable water supplies, and decentralised options may be more suitable. Therefore improved house hold point-of-use disinfection technologies are urgently needed. Current practices require large energy inputs and chemicals or training. Combining LED and photovoltaic technologies together has the potential to sustainably overcome many of these barriers [1].

2. MATERIALS AND METHODS

2.1 Experimental setup

A bench scale apparatus were used for testing the efficiency of LED disinfection. It consists of 6 cm diameter sample holder and LED module. LED module consists of nine LEDs arranged in square array. Square array was formed by soldering the nine bulbs to a dot circuit board. The bulbs were soldered in parallel connection, so that power of 3 volts reaches equally in to each bulb. The bulbs were placed 1 cm apart on the circuit board. All the nine bulbs were soldered on to a 4 cm * 4cm circuit board.Sample container is Borosilicate glass jar of 250 mL capacity. Sample container has 6 cm diameter and height 8.5 cm. The sample containers were covered with aluminum foil to prevent the light from scattering to outside, so that applied light is internally reflected inside the container.

The LED array is fixed to PVC frame, so that the height of LED array above the sample can be controlled. A DC power supply of 3 volts was applied to the LED array. Light can be applied from the top of container.The LED array was adjusted to 1 cm above the sample solution. Minimum transmittance of light through water at 300 nm-700 nm is 99% per 10 cm [3]. Here the total length of light travel was less than 10 cm, so that nearly complete transmittance of applied light was assured. After pouring the sample to the container the height of LED array were adjusted to required height. Three number of identical bench scale apparatus and containers were used, each one for White LED, Blue LED and UV-A LED respectively, so that inactivation experiment can be conducted simultaneously. Fig. 2 shows the bench scale experimental setup, which was used for bacterial inactivation experiments.

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Figure 2 Bench scale experimental setup

2.2 Experimental Design

Particular sample was irradiated using different types of wavelengths. The UV-A LED module had peak emission of 395 nm, White LED module had peak emission of 450 nm, and Blue LED module had peak emission of 470 nm. Water sample depth used for irradiation, and time of irradiation are constraints that affect bacterial inactivation. So the experiment was repeated for varying depth, time of irradiation.The experimental testing scheme is shown in Table 1.

Table 1 Experimental testing scheme

Disinfection scheme	Parameter	Variable range
Blue LED/White LED/UV-A LED	pH	6.5
	Turbidity	6 NTU
	Sample depth	0.50 cm and 0.75 cm
	Exposure time	1 – 5 hours

2.3 Microbiological Analysis and Result representation

Indicator organisms are commonly tested instead of pathogens as an indication of water contamination. One group of indicator bacteria is the coliform bacteria, which are operationally defined as Gram-negative, non-spore-forming, aerobic and facultative anaerobic bacteria that ferment lactose and produce acid and gas. The faecal coliform sub group of the total coliforms is a much more specific indicator of the fecal contamination.

The simplest and the most recent method adopted for detecting and measuring the presence of coliform bacteria is to filter the water sample through a sterile membrane of special design (porosity 80 %, pore size 5 to 10 milli

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micron), on which the bacteria will be retained. Then the filter is placed on suitable nutrient medium, and incubated at an appropriate temperature and time. For faecal coliforms count, the medium to be used is M-FC broth and incubation is done at 44.5^{0}C for 22 hours [8]. The coliform colonies here are blue, and the other bacteria which grow upon this medium are grey to cream coloured. For each sample, a minimum of 3 dilutions was sent for microbiological analysis. The untreated water samples were diluted to 10^{-3}, 10^{-4}, and 10^{-5}. The treated samples were diluted to 10^{-1}, 10^{-2}, and 10^{-3}. The dilution series was carried out by diluting 1 mL of the sample into a test tube containing 9 mL of sterilized water. This resulted in a 10^{-1}sample. Next, 1 mL of the 10^{-1}sample was diluted into another test tube containing 9 mL of sterile water, which resulted in a 10^{-2}sample. This was continued to reach the necessary dilutions. Plates with colonies in the range 20-60 were taken for calculations.

The colony forming units per mL (CFU/mL) of the sample was determined by the following expression [4]:

$$\frac{CFU}{mL} = \frac{\text{No. of colonies}}{\text{Dilution factor} \times \text{Amount plated}} \quad (1)$$

The inactivation rate was expressed as per the following relation [4]:

$$\text{Log reduction} = \log_{10} \frac{I}{F} \quad (2)$$

Where, I is the initial no. of microorganisms, and F is the final no. of microorganisms.

2.4 Sample preparation

Since bacterial inactivation analysis is the main objective, it is required to create a higher bacterial population before the irradiation experiments. For that bacteria were cultivated artificially by using cow dung. Test strains from 1gm of cow dung were inoculated into 500 ml of water and cultivated at 37^{0}C under rotary conditions at 125 rpm. After an 18-hour incubation period, the suspension was then diluted to the required starting bacterial population for experimental use [9]. Sample was placed in the container, with required initial qualities. Then the LED array was fixed to 1 cm above the sample surface. Then the sample was irradiated using LED module. After required time of treatment final bacterial population of sample was analyzed.

III. RESULTS AND DISCUSSION

The properties of sample after spiking it with cow dung stock solution are as shown in Table 2. Fig. 3 shows the cultivated petridishes after incubation.

Table 2 Spiked water sample quality

Parameter	Value
Turbidity	6 NTU
Temperature	30.9^{0}C
pH	6.5
TDS	71.6 ppm
DO	6.2 mg/L

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TSS	93.2 mg/L
Faecal coliforms	100000 CFU/ml

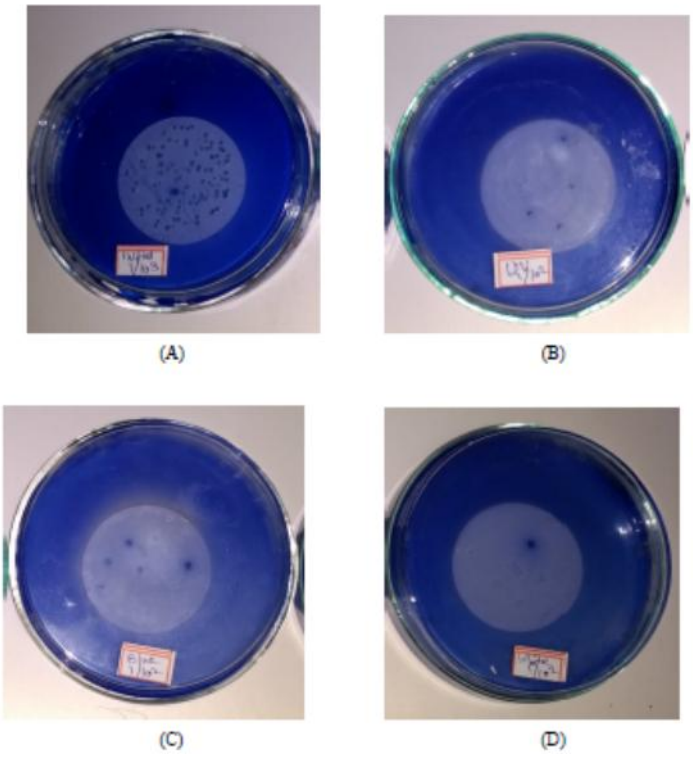

Figure 3 (A) bacterial colonies present in initial water sample, (B) bacterial colonies present in water sample after treating with UV-A LEDs, (C) bacterial colonies present in water sample after treating with Blue LEDs, and (D) bacterial colonies present in water sample after treating with White LEDs

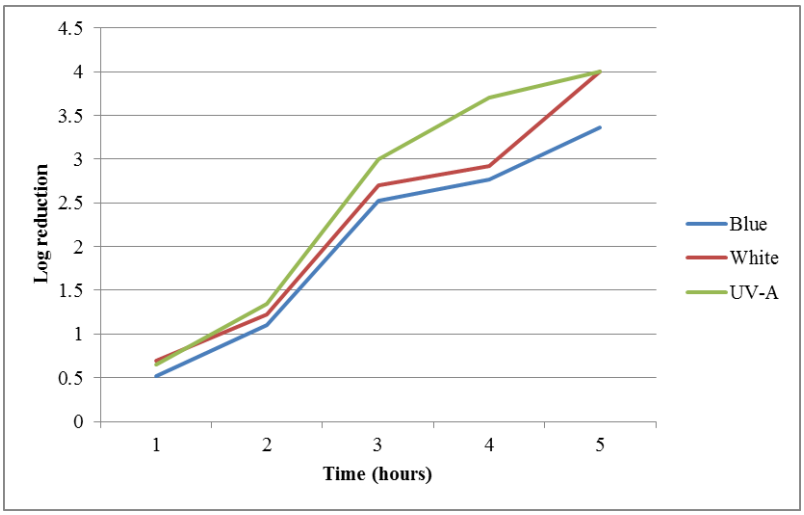

Figure 4Variation of log reduction with respect to treatment time with 0.75 cm sample depth

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Fig. 4 shows the variation of log reduction with respect to treatment time when sample depth is fixed as 0.75 cm. White and UV-A LEDs treatment achieved a 4 log reductions within 5 hours. Blue LEDs treatment achieved 3.36 log reductions within those 5 hours.

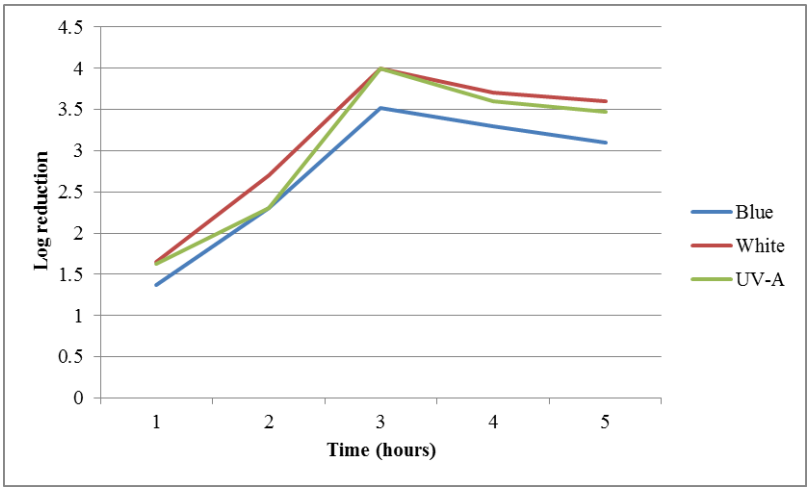

Figure 5Variation of log reduction with respect to treatment time with 0.50 cm sample depth

Fig. 5 shows the variation of log reduction with respect to treatment time when sample depth is fixed as 0.50 cm. White and UV-A LEDs irradiation on water sample produced a 4 log reductions within time treatment of 3 hours. Within those 3 hours the Blue LEDs irradiation produced 3.52 log reductions of faecal coliforms in the water sample. But after the 3 hours there is no significant change in bacterial population was observed for the particular water depth of 0.50 cm.

Light intensity in terms of Lux was measured using a digital light meter. Then the Lux was converted to mJ/cm^2 as perphotometric to radiometric conversion. Table 3 shows the applied light dose to water sample by different LED modules.

Table 3 Applied light dose to water sample by different LEDs

Time of treatment (hours)	Dosage of irradiation by Blue LEDs (mJ/cm^2)	Dosage of irradiation by White LEDs (mJ/cm^2)	Dosage of irradiation by UV-A LEDs (mJ/cm^2)
1	1260	2556	313
2	2520	5112	626
3	3780	7668	939
4	5040	10224	1252
5	6300	12780	1566

VI. CONCLUSION

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Treatment of water sample having a depth of 0.75 cm by using UV-A LEDs and White LEDs achieved a 4 log reduction in faecal coliforms within 5 hours. Treatment using Blue LEDs also showed 3.36 log reduction of faecal coliforms within 5 hours of irradiation treatment. UV-A and visible LEDs have potential to inactivate faecal coliforms. But major limitation is that larger time is required for inactivation. Similarly, when the depth of water sample is reduced to 0.50 cm the LED treatment failed to give a consistent bacterial inactivation.

It has been found that a dosage > 1000 mJ/cm^2 from UV-A module is required for better inactivation of microorganisms. So LEDs having higher optical output may give good inactivation of microorganisms within a short time of treatment. So works on disinfection of water with LEDs capable of producing larger irradiation dosage can be studied in future.

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