Design and evaluation of zero-energy UVC-LED reactor fitted with hand pump system for disinfection

Kaviya Piriyah Sundar and S. Kanmani

ABSTRACT

The main source of drinking water for rural communities in India is rainwater harvesting ponds. These ponds do have a sand filtration system for turbidity removal, but the bacteriological quality of these ponds is not under compliance in most cases. In this context, Pattikadu village in Kancheepuram District (Tamil Nadu, South India) was chosen as the study area. It was observed that the biological parameter of drinking water from hand pumps exceeds the limit prescribed by Indian standards. In this work, zero-energy disinfection technology was developed using UVC-LEDs for drinking water to meet the standards. The electrical power required for the disinfection was taken from the mechanical energy from up and down movement of the hand pump lever. UVC-LEDs ($\lambda_{emission}$ 275 ± 5 nm) were powered by a 6 V rechargeable battery which stores electrical energy by mechanical movement of the hand pump lever. An annular-type UVC-LED photo-reactor (1 litre) was developed and 100% disinfection within 6 minutes' contact time was achieved. The UVC dose-based inactivation rate constant was 0.57 cm^2/mJ. The present study demonstrated 2-log inactivation for a 4.68 mJ/cm^2 UVC dose. The novelty of the study is its practical applicability of a sustainable point-of-use disinfection technology which might be economically implemented in lower-income smaller communities.

Key words | drinking water, most probable number, photo-reactor, UVC-LED disinfection, zero-energy technology

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HIGHLIGHTS

- Zero energy water disinfection technology was developed for rural villages, where mechanical energy of hand pump operation was converted into electrical energy.
- 100% removal of E.coli was achieved within 6 minutes disinfection time (inactivation constant as 0.57 cm^2/mJ).
- Two stage decay curve shows that in the first 3 minutes there was fast decay of 93% bacterial population (rate constant 0.52 cm^2/mJ).

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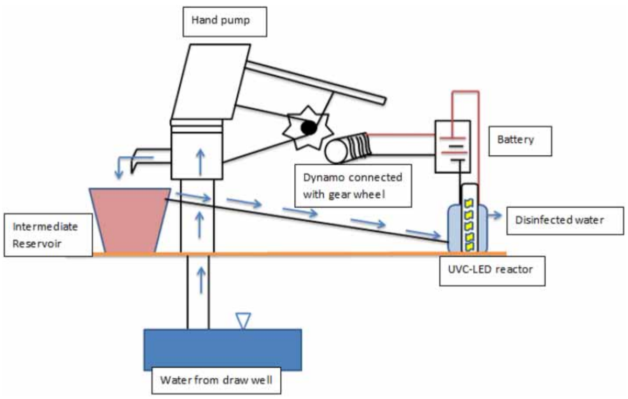
GRAPHICAL ABSTRACT



INTRODUCTION

India has experienced an enormous growth in population and mainly relies on the use of rainwater harvesting for drinking purposes. India, being a monsoon country, receives rainfall for only three to four months in a year, but it is not evenly distributed in all places. As rainwater harvesting is deeply rooted in South Indian history, so-called 'Ooranies' or large water ponds are still likely to be found all over the rural areas. There may be the existence of pathogenic contamination which requires an advanced level of treatment for these water sources before consumption. Disinfection is one of the most effective methods to reduce the number of waterborne diseases caused by pathogenic organisms. Availability of clean and safe drinking water at the doorstep of the ordinary person is still a need of the hour.

'Ooranies'/large water ponds are one of the main sources to cover the drinking water demand in villages in South India (IWWA 2020). They collect the rainfall runoff and preserve it as a drinking water source for the village throughout the year. Hence, it is an annual storage facility. In general, oorani water is found to have a high turbidity and bacterial count. The pre-treatment (sand filtration) applied removes the turbidity, but often an appropriate disinfection step is lacking in the drinking water system of South Indian villages. Hand pump is the major drinking water point-of-use for the communities in the villages. Out of the total hand pump users (996 million), 80% of them are from rural populations (UNICEF 2012).

Chorine-based disinfection is the common method for removal of pathogenic organisms in drinking water, usually the final treatment before consumption (Yoo 2010). Different disinfection methods known so far are: boiling, bio-sand filtration, chlorination, ozonation, UV and solar photolysis (Sobsey *et al.* 2008). Process efficiency of UV treatment is high, but the major drawbacks are the presence of mercury content, the cost of electrical energy and frequent replacement of the conventional UV mercury lamp which has a lower life period (Chatterley & Linden 2010). Many works have focused on the use of UV-LEDs for disinfection, which is energy efficient and free of toxic substances (Song *et al.* 2016; Li *et al.* 2019). One of the disadvantages of UV disinfection is the revival of microorganisms in darkness after treatment, whereas higher UV intensity and lower exposure time minimises the microorganisms revival in darkness (Chen *et al.* 2020). On the other hand, cost and energy efficiency are to be considered as well. Energy efficiency might be achieved by optimising the UV dose per log inactivation with varying wavelength. Wavelength of 260 nm could effectively absorb DNA molecules resulting in pyrimidine dimers, pyrimidine hydrates and crosslinks between proteins and DNA, but it was reported by Takahashi *et al.* (2020) that the microorganisms could dark repair their DNA. In contrast, it was reported that at 280 nm, protein absorption was at its peak which leads to disruption of enzymes that favour dark revival (Song *et al.* 2016). Also, an important challenge for the UV-LED disinfection technique is the cost factor, especially among low-income groups. Therefore, an economically feasible and self-sustaining disinfection system is required, which is the reason wavelength ~280 nm was chosen for the present study.

In the present study, Pattikadu village in Kanchipuram district (Tamil Nadu, South India) was chosen as the study area. The Oorani water (raw water) was found to be highly turbid (~50 NTU) and with the presence of *Escherichia coli* bacteria (~2,400 CFU/mL). It was observed that after sand filtration, turbidity (~2 NTU) significantly reduced, but the biological parameter (~133 CFU/mL) did not comply with the drinking water quality standards (BIS 10500:2012). Therefore, disinfection prior to consumption of water was mandatory, for which, zero-energy technology for removal of pathogenic organisms was designed. UVC-LED disinfection was evaluated for the developed annular photo-reactor which was fitted with the hand pump of Pattikadu village (study area). The mechanical energy was conserved and stored as electrical energy to serve as the power supply for energising the UVC-LEDs. The developed model would be zero-energy technology for practical applicability in rural areas.

MATERIALS AND METHODS

Sample collection

Water samples from the hand pump were taken from Pattikadu village (Figure 1, adopted from Google map images and Figure 2), located in Tirukalukundram Block of Kancheepuram district in Tamil Nadu, South India. The total

Figure 1 | Map of the study area.

Figure 2 | Pattikadu Village and Oorani.

geographical area is around 294 hectares with a total population of 1,050 people (Wikivillage 2020). The pre-treatment of Pattikadu oorani consists of a multi-barrier system (Figure 3, adopted from Government of Tamil Nadu Rural Development for Rejuvenation of Ooranies). The multi-barrier system contains a catchment area, supply channel, grit chamber, oorani storage, filter chamber, water supply pipe, fine sand filter and draw well. The grit chamber with a baffle wall traps the grit particles and prevents floating solids entering the catchment. Oorani serves as an aerobic pond where microbiological processes take place under aerobic conditions. In the horizontal roughing filter, larger organics and inorganics are removed. Further water is pumped to a fine-sand filter removing turbidity and coliforms and withdrawn from the hand pump for use. The raw water was collected from the water spread area (Oorani) (No. 4 in Figure 3). The fine sand-filtered water was collected from the draw well (No. 6 in Figure 3).

Each 10 L of raw and sand-filtered water samples before and after monsoon rains were collected and analysed within 48 hours of collection for accurate results. Table 1 reports the date and time of sample collection.

Figure 3 | Scheme of rainwater harvesting (Ooranies) by Government of Tamil Nadu for villages (https://tnrd.gov.in/oorani/index.php).

Table 1 | Sample collection dates and time

Season	Date	Time (IST)
Before monsoon rains	10/05/2019	11:30 a.m.
	24/05/2019	3:00 p.m.
After monsoon rains	30/07/2019	11:00 a.m.
	25/11/2019	2:00 p.m.
	27/08/2020	3:30 p.m.

UVC-LED characterisation

The UVC-LEDs with nominal peak emission at 275 ± 5 nm that were adopted by previous literature survey demonstration proved that the highest *E. coli* inactivation occurred at 275 nm rather than 255 or 310 nm (Aoyagi *et al.* 2011; Oguma *et al.* 2013). The emission spectrum was determined by fibre optic spectrometers (StellarNet EPP 2000) and by SpectraWiz. The values are derived from the source and plotted as a graph between intensity and wavelength. The maximum intensity count was observed at 275 nm from the plotted graph (Figure 4). Each UVC-LED was operated at 20 mA constant forward current, 5.5 V forward voltage, viewing angle 120° and radiant flux of 0.0937 mW for each LED, according to the manufacturers' details.

Experimental setup

An annular UVC-LED photo-reactor (capacity 1 litre) was designed for batch process. 24 UVC-LEDs were connected in parallel and placed inside a quartz tube of diameter 30 mm and length 300 mm. The quartz tube was fitted inside an enclosure made of stainless steel of diameter 87 mm and length 240 mm and thickness 2 mm. The distance between the light source and nearer/farther side of the water medium was 1.5 and 2.75 cm, respectively. A schematic diagram of the UVC-LED reactor and lamp image is shown in Figure 5.

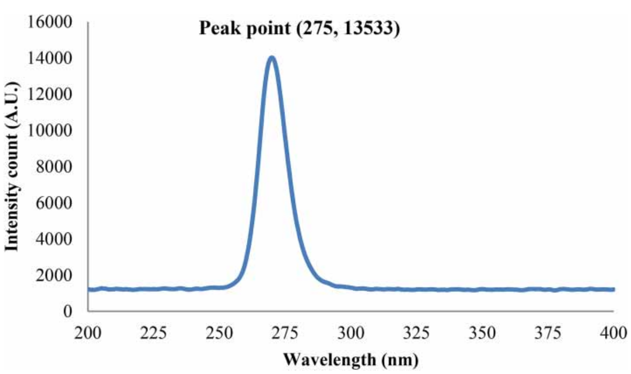


Figure 4 | Emission spectrum of UVC-LED.

The hand lever of hand pump Mark II was welded with the necessary support angles at appropriate places to achieve the full rotation of the circular plate, where the plate rotates with the mechanical up and down movement of the hand lever (Niroopa & Kanmani 2015). The circular plate was connected to the large gear wheel which was connected to the dynamo through a small gear wheel. One rotation of the larger gear wheel induces the smaller gear to rotate ten numbers of revolutions. On average, in 1 minute, 60 strokes (up and down movement of lever) can be generated by a person. The mechanical energy of the gear wheel was converted into electrical energy through a dynamo. The dynamo consists of stator coils and rotor magnet, generating AC current through Faraday's law of induction. The dynamo was connected to the 6 V DC battery through a bridge rectifier. The voltage generated by the hand pump lever produced 600 revolutions in the small gear wheel per minute, which was enough to charge a 6 V battery. The experimental setup of the hand pump is shown in Figures 6 and 7.

Energy balance

In general, an average person produces 60–80 strokes in a hand pump for a minute. Therefore, when the energy balance is computed, the force applied to the hand lever creates the rotational energy in the larger gear wheel. The ratio between the radius of the larger wheel and smaller wheel is 10. The number of revolutions increases to 600 in the smaller gear wheel. The rotations of rotor magnet in the dynamo cause a change in magnetic flux. The current is induced in the stator coil by Faraday's law of induction by change of magnetic flux. Electromotive force is energy generated per unit charge. A multi-meter recorded a minimum of 6 V and 20 mA when the hand pump was operated for each stroke. The temperature difference (ΔT) of water before and after disinfection was recorded to be 1.5 °C for 6 minutes of reactor operation.

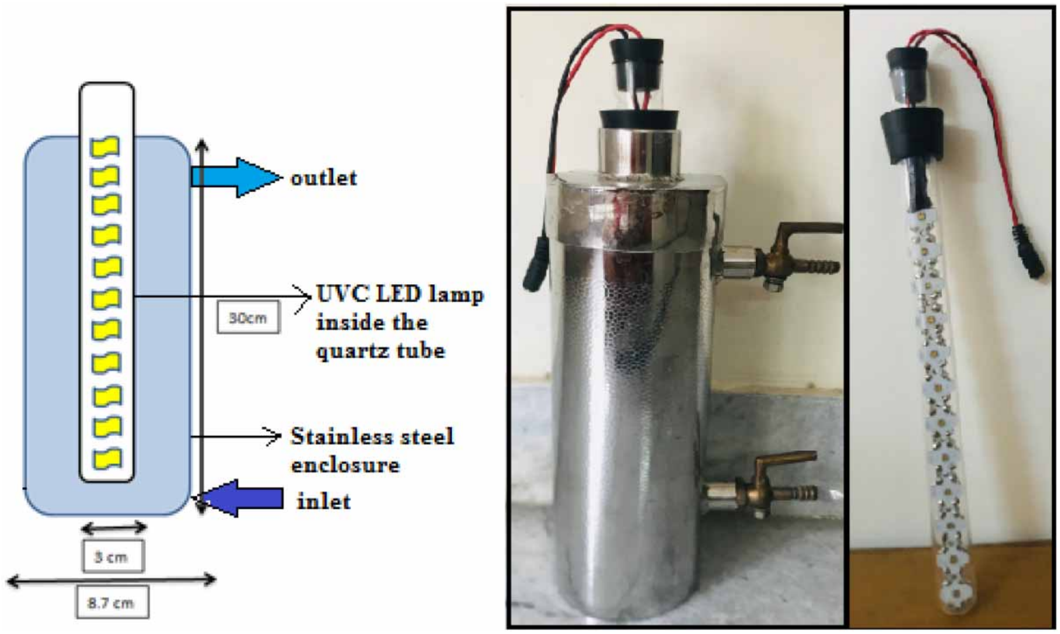


Figure 5 | Schematic diagram and photo of UVC-LED reactor.

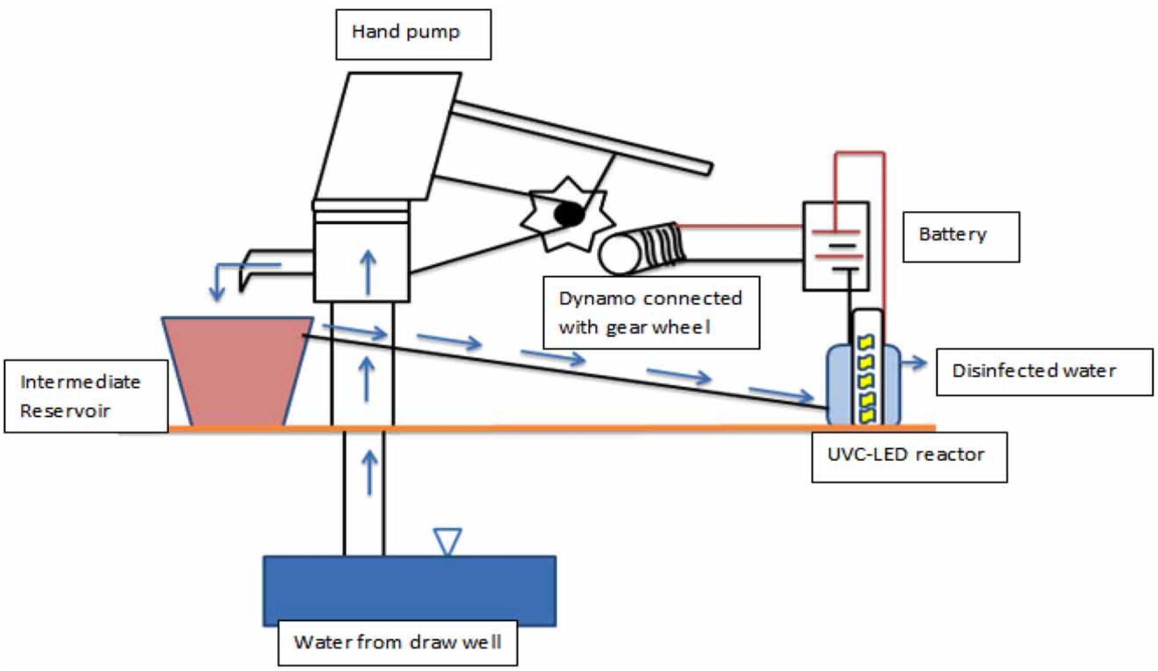


Figure 6 | Hand pump fitted with zero-energy UVC-LED reactor setup.

Figure 7 | Hand pump fitted with gear wheels and dynamo.

The energy balance at the UVC-LED reactor is computed as in Equation (1):

$$\text{Energy produced at hand pump (1 minute)} = \text{Energy from LED irradiance} + \text{Energy spent for heating} \quad (1)$$

$$\text{Power produced per stroke} = \text{Voltage generated} \times \text{current} = 6\ \text{V} \times 20\ \text{mA} = 120\ \text{mW per second}$$

$$\text{Energy produced by hand pump for 1 minute} = 120\ \text{mW} \times 60\ \text{sec} = 7{,}200\ \text{mJ}$$

$$\text{Energy spent in heating of water (experimental)} = c \times g \times \Delta T = 4.186\ \text{J/g}^\circ\text{C} \times 1{,}000\ \text{g} \times 1.5^\circ\text{C} = 6{,}279\ \text{mJ}$$

where c is the specific heat capacity of water, g is the mass of water and temperature difference (ΔT) is 1.5 °C.

$$\text{Radiant energy from UVC-LEDs} = 7{,}200\ \text{mJ} - 6{,}279\ \text{mJ} = 921\ \text{mJ}$$

$$\text{Radiant power from 24 LEDs} = 2.25\ \text{mW}$$

$$\text{Irradiance time} = \text{Radiant energy/Radiant power} = 409\ \text{sec} = 6.8\ \text{minutes}$$

Therefore, 1 minute of mechanical movement of the hand pump is sufficient for a minimum 6 minutes of UVC-LED irradiation.

Test methods

pH

pH was measured by pH meter according to IS 3025 (Part 11) 1983 (RA 2012). The instrument was standardised with two buffer solutions of pH near that of the sample and a different pH value. Temperature was measured and adjusted accordingly. The electrode was washed and immersed in the sample beaker to record the sample pH.

Temperature

Water temperature was measured by digital thermometer according to IS 3025 (Part 9) 1984. This was done by dipping the thermometer into the sample and recording a stable reading.

Turbidity

Turbidity was measured by a turbidimeter according to IS 3025 (Part 10) 1984 (RA 2017). First, the instrument was checked for accuracy in calibration with standards. Then, the sample was shaken to achieve uniform dispersion and poured onto the turbidimeter tube to record the turbidity value.

Total suspended solids

Total suspended solids (TSS) were estimated by gravimetric method according to IS 3025 (Part 17) 1984 (RA 2017). First, the weight of a clean dried glass fibre filter of diameter 5.5 cm and pore size 1.2 μm (Whatman GF/C) was measured. Next, 1 L of sample was filtered using suction through the glass fibre filter and then the filter was dried at 105 °C for 1 hour, subsequently cooled in a desiccator for half an hour and weighed immediately. The TSS value was calculated as in Equation (2):

$$TSS\left(\frac{mg}{L}\right) = \frac{M_f - M_i}{V} \times 1{,}000 \quad (2)$$

where M_f is final mass of filter (after filtration) in mg, M_i is initial mass of filter (before filtration) in mg and V is volume of sample in mL.

Total dissolved solids (TDS)

TDS were measured using gravimetric method according to IS 3025 (Part 16) 1984. A portion of water was filtered using a glass fibre filter of diameter 5.5 cm and pore size 1.2 μm (Whatman GF/C) and 10 mL of the filtrate was added to a pre-weighed clean evaporating dish. The complete water was evaporated in an oven at a temperature of 98 °C for 3 hours. Then, the remaining residue was transferred to 105 °C for 1 hour, to attain constant mass. The dish was cooled in a desiccator and was weighed. The TDS was calculated as in Equation (3):

$$TDS\left(\frac{mg}{L}\right) = \frac{M_2 - M_1}{V} \times 1,000 \quad (3)$$

where M_2 is final mass of residue and evaporating dish (after filtration and evaporation) in mg, M_1 is empty weight of clean evaporating dish in mg and V is volume of sample in mL.

Electrical conductivity

Electrical conductivity was measured using a pre-calibrated digital conductivity meter. The probe was dipped into the water samples until a stable reading was obtained.

Standard plate count

The pour plate method was followed according to IS 14648: 2011. In sterile Petri dishes, 1 mL of the sample was poured into 20 mL of nutrient agar medium. The suspension was mixed with medium by tilting the plates slowly. After solidification, inoculated plates were inverted and incubated at 30 °C for 3 days and colonies were counted. Serial dilution was done until 30–300 colonies were observed in a single plate for quantitative estimation and all experiments were performed six times independently including the duplicate plates.

RESULTS

Initial characterisation

Parameters were analysed for the collected raw water and sand-filtered water before and after monsoon. Table 2 shows the water quality parameters for raw and sand-filtered water before and after monsoon. It was observed that turbidity and microbial concentration is comparatively low before monsoon, but after rain, the turbidity, total suspended solids

Table 2 | Raw and sand-filtered water characteristics (before and after monsoon)

	Average of samples				
Parameter	**Raw water (BM)**	**Sand-filtered water (BM)**	**Raw water (AM)**	**Sand-filtered water (AM)**	**Standards**
pH @ 25 °C	6.9 ± 0.1	6.8 ± 0.3	7.4 ± 0.06	7.3 ± 0.35	6.5–8.5
Water temperature (°C)	28.8 ± 0.75				–
Turbidity (NTU)	1 ± 0.1	0.5 ± 0.3	54 ± 2.4	2 ± 1.6	1–5
Total suspended solids (mg/L) @ 105 °C	13 ± 3.2	2.5 ± 0.22	235 ± 17	146 ± 32	500
Total dissolved solids (mg/L)	72 ± 5.5	68 ± 2.9	95 ± 3.6	100 ± 8.2	500–2,000
Electrical conductivity (μS/cm)	147 ± 4.3	146 ± 2.9	205 ± 2.5	207 ± 6	–
Standard plate count (CFU/mL)	141 ± 9	25 ± 5	2,400 ± 111	133 ± 8	Nil

BM, before monsoon; AM, after monsoon.

and microbial concentration values increased, whereas total dissolved solids and electrical conductivity showed a slight increase due to dissolution of inorganic ions because of rain-water surface run-off. All the parameters were analysed three times independently. The values reported are means with standard deviations of the values for the respective parameters. The sand-filtered water (after monsoon) was used for disinfection studies in the present work.

DISCUSSION

The disinfection efficiency is shown in Table 3 and Figure 8, where the initial colonies count was 133 ± 8 CFU/mL. With the exposure to UVC-LED irradiance, the colony counts reduced significantly with time resulting in <1 CFU/mL. The standard plate count values reported are means with standard deviations of the three repeatable values.

In the kinetic analysis, the log inactivation versus UVC dose follows the first-order model. Thus, UVC dose-based inactivation rate constants were defined as in Equation (4) (Oguma *et al.* 2016):

$$\log\left(\frac{No}{N}\right) = k \times \text{UVC dose} \quad (4)$$

where k is the UVC dose-based inactivation rate constant, N is the number of surviving cells after disinfection exposure time of t (seconds) and No is number of initial cells before disinfection.

From Figure 9, the value of k (0.57 cm^2/mJ) was obtained from the slope of linear regression models

Table 3 | Log reduction of different disinfection time

Disinfection time (minutes)	UVC-dose (mJ/cm^2)	Standard plate count (CFU/mL)	Log (*N*/No)
0	0	133 ± 8	0
1	0.78	123 ± 5	−0.034
2	1.56	73 ± 3	−0.26
3	2.34	15 ± 3	−0.98
4	3.12	4 ± 2	−1.52
5	3.9	2 ± 1	−1.8
6	4.68	< 1	−2.1

($R^2 = 0.97$). The sensitivity of bacteria to UVC radiation was evaluated by UVC dose-based inactivation rate constant (slope of log inactivation and UVC dose). The obtained k value is comparable with past studies (Chatterley & Linden 2010), where the k for *E. coli* inactivation varied from 0.17 to 0.422 cm^2/mJ.

The germicidal efficiency of UV disinfection is majorly influenced by the emission wavelength but not the spectral sensitivity of target organisms (Chen *et al.* 2009). Even though the peak absorption of *E. coli* is around 260–265 nm, 275 nm proved to be efficient in terms of UV dose per log inactivation (Bowker *et al.* 2011). So far, UV disinfection works have been carried out using different wavelengths (315–400 nm (UVA), 280–315 nm (UVB) and <280 nm (UVC)). In general, at higher wavelength (365 nm or 310 nm), the UV dose-response required was higher due to the higher values of output energy of UVA and UVB-LEDs. On the other hand, lower wavelength (255 nm or 275 nm) requires least UV dose-response due to lesser output energy of UVC-LEDs. Hamamoto *et al.* (2007) demonstrated a higher value of 55,263 mJ/cm^2 UV dose was required for per log inactivation, where the emission wavelength was 365 nm. Similar work was carried out by Mori *et al.* (2007), who applied 365 nm for *E. coli* inactivation which required 13,846 mJ/cm^2 as the UV dose per log inactivation (Song *et al.* 2016). Bowker *et al.* (2011) applied 255 and 275 nm radiation for 1 log *E. coli* inactivation which required 3.3 and 2.4 mJ/cm^2. In this work, 2.23 mJ/cm^2 of UVC dose was required per log inactivation which proves to be more efficient than other works have reported so far. Further 2 log inactivation was obtained at 6 minutes under UVC dosage of 4.68 mJ/cm^2, and similar results were found in the literature (Chang *et al.* 1985; Vilhunen *et al.* 2009). Shorter disinfection time and higher UV dose is desirable for *E. coli* inactivation due to photochemical and biological processes (Harm 1980).

When plotting the survival population ratio and UVC dose-response curve (Figure 10), it was observed that there is a decline in survival of *E. coli* count with increasing UVC dose. The graph fits with the two-stage decay pattern, where initially the rate of inactivation was faster ($k_1 =$ 0.52 cm^2/mJ); furthermore, the rate of inactivation was slow ($k_2 = 0.014$ cm^2/mJ). The two-stage decay is the sum of a rapid decay curve of the majority population followed

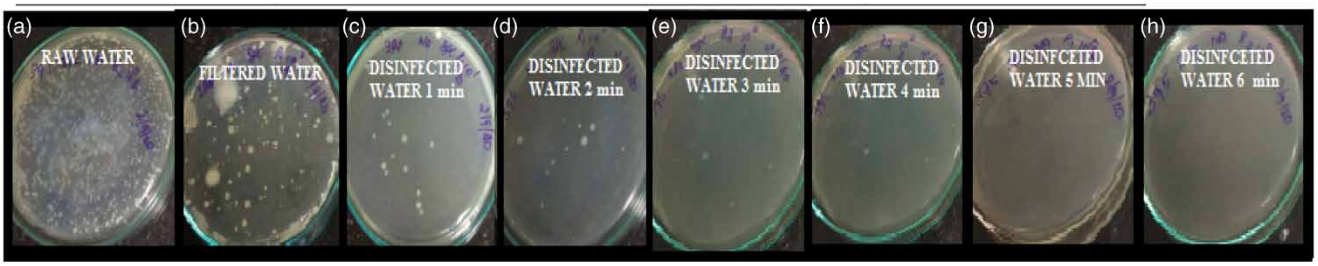


Figure 8 | Results of the *E. coli* disinfection (a) 2,400 ± 111 CFU/mL for raw water after monsoon, (b) 133 ± 8 CFU/mL for sand-filtered water after monsoon, (c)123 ± 5 CFU/mL (with 0.78 mJ/cm^2 UVC dose), (d) 73 ± 3 CFU/mL (with 1.56 mJ/cm^2 UVC dose), (e) 15 ± 3 CFU/mL (with 2.34 mJ/cm^2 UVC dose), (f) 4 ± 2 CFU/mL (with 3.12 mJ/cm^2 UVC dose), (g) 2 ± 1 CFU/mL (with 3.9 mJ/cm^2 UVC dose), (h) <1 CFU/mL (with 4.68 mJ/cm^2 UVC dose).

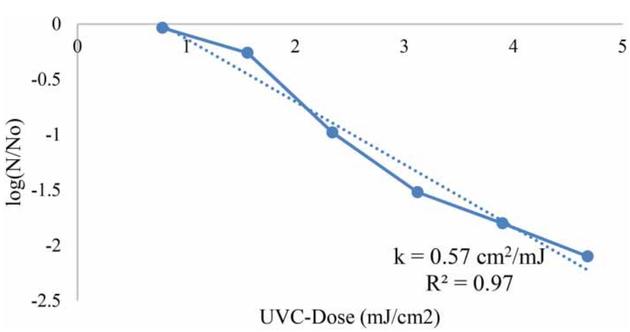


Figure 9 | Inactivation profiles with UVC dose.

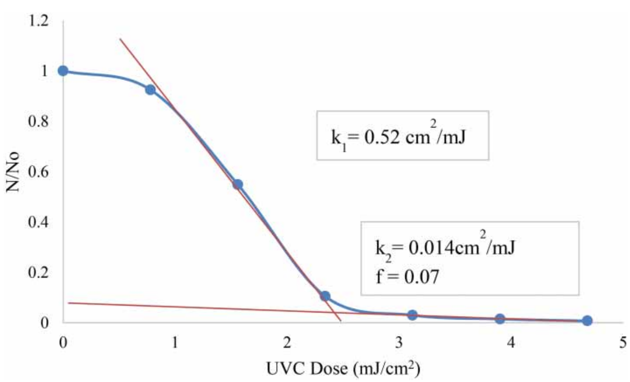


Figure 10 | Plot of bacterial survival and UVC dose.

by a slow decay curve of the resistant minority population. Initially, the fast decay fraction $(1-f)$ of bacteria gets easily deactivated and later the resistant fraction (f) creates the tailing effect. The majority population of 93% deactivates faster, within the initial 3 minutes, and the remaining 7% population which is resistant dies in another 3 minutes (Kowalski *et al.* 2020). Equation (5) defines the survival fraction (N/No) of microorganisms using the two-stage model:

$$N/No = fe^{-k_2 D} + (1 - f)e^{-k_1 D} \quad (5)$$

where k_1 is the rate constant for the first population, k_2 is the rate constant for the second population and D is the UVC dose (mJ/cm^2).

CONCLUSIONS

In this present work, the UVC-LED (λemission 275 ± 5 nm) reactor for disinfection was designed for rural areas, where hand pump is the major point-of-use for the small community population. The electrical power required for the disinfection was taken from the mechanical energy from up and down movement of the hand pump lever. The 6 V rechargeable battery was charged by 1 minute operation of the hand pump (60–80 strokes). The UVC-LED batch annular reactor (capacity 1 L) fitted with the hand pump showed that in 6 minutes of disinfection time, 100% *E. coli* inactivation was observed. The UVC dose-based inactivation rate constant obtained was 0.57 cm^2/mJ. The survival UVC dose graph shows that the two-stage decay model is the best model fit for the present work. The novelty of the study is the use of high-end water treatment technology for lower-income groups with zero-energy requirement. In future, the reactor may be evaluated for higher throughput with other UV disinfection methods, including UVA/UVC combined treatment, UVA/TiO_2 photo-catalytic disinfection or pulsed UV disinfection.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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