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Design and implementation of a water treatment system using ultraviolet radiation (UV) produced with photovoltaic energy

Diseño e implementación de un sistema de tratamiento de agua aplicando radiación ultravioleta (UV) alimentada con energía fotovoltaica

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Abstract

The objective of this research study was to design and implement a water treatment system using ultraviolet radiation (UV) produced with photovoltaic panels. This system would be able to satisfy the needs of residents who do not have drinking water and live in rural areas. The design begins with the evaluation of the energy demand required for the ultraviolet light lamp and the water pump, which are powered by the photovoltaic panel. The system consists of a tank for water collection, a DC12V pump, a pre-filter and a filter for sediments, an activated carbon filter, a UV-C light lamp and a storage tank. Mandatory control parameters according to DIGESA were evaluated such as pH, color, turbidity, thermotolerant and total coliforms present in the water, before and after the treatment. The results obtained demonstrate that the system works efficiently. The observed values were lower than the maximum permissible limits for the physicochemical and microbiological analysis. For total and thermotolerant coliforms, 0 CFU / 100 mL were found, demonstrating that UV-C radiation completely eliminates the microorganisms present in water.
Keywords: Ultraviolet radiation, photovoltaic panel, total coliforms, thermotolerant coliforms.

Resumen

El objetivo del presente trabajo de investigación fue diseñar e implementar un sistema de tratamiento para agua aplicando radiación ultravioleta (UV) alimentada con paneles fotovoltaicos, dicho sistema podrá satisfacer la necesidad de pobladores que no cuentan con agua potable y radican en zonas rurales. El diseño empieza con la evaluación de la demanda energética requerida para la lampará de luz ultravioleta y la bomba de agua, alimentada con el panel fotovoltaico. El sistema consta de un tanque para la captación del agua, una bomba DC12V, un prefiltro de sedimentos, filtro de sedimentos, filtro de carbón activado, lampara de luz UV-C y tanque de almacenamiento. Se evaluaron parámetros de control obligatorio según DIGESA como pH, color, turbiedad, coliformes totales y termotolerantes presentes en el agua, antes y después del tratamiento. Los resultados obtenidos demuestran que el sistema funciona eficientemente se obtuvieron valores dentro de los límites máximos permisibles para el análisis fisicoquímico y microbiológico se obtuvo 0 UFC/100 mL para los coliformes totales y termotolerantes, demostrando que la radiación UV-C elimina completamente los microorganismos presentes en el agua.
Palabras clave: Radiación ultravioleta, panel fotovoltaico, coliformes totales, coliformes termotolerantes.

1 Introduction

The global water crisis is one of the biggest problems faced by various countries, and various proposals on water management are currently being made. For the World Health Organization (WHO), the innocuity and quality of water are fundamental for human development and well-being. Providing access to clean and safe drinking water is one of the most effective instruments for promoting health and reducing poverty (OMS, 2017).

Water treatment technologies for rural areas require technical skills, materials and infrastructure (labor, appropriate facilities, electricity, chemical reagents, operation and maintenance staff) and financial capabilities (investment, operation and maintenance costs) which availability depends strongly on the capacity of the community and the level of support provided by regional institutions accountable for water and health matters.

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In addition, the community should be involved in the planning, selection, design, construction, administration, operation and maintenance of treatment systems so that the operation of the facilities occurs in an appropriate manner and is sustainable (Gonzáles *et al*., 2013).

Several methods for home water treatment in order to remove microorganisms and turbidity exist. These methods are based on heating (boiling water, solar radiation, UV lamps), chemical treatments, physical removal (filters), among others. The use of home treatment systems by rural communities, such as slow sand filters, ceramic candle filters, membrane filters, ceramic pots, has been evaluated all over the world (Perez-Vidal *et al*., 2016).

For the water to be suitable for human consumption, a series of treatments is required according to its initial quality. All treatments have limitations and advantages depending on the field of application. Among them, we have; a) conventional filtration: sand filters, diatomaceous earth filters and activated carbon filters; b) disinfection: chlorine, chloramine, ozone, ultraviolet light; and c) membrane filters: microfiltration, ultrafiltration, nanofiltration, reverse osmosis (Leal Ascencio, 2005).

The presence of fecal coliforms in water is very often used as an indicator of fecal contamination. Other parasites such as Giardia lamblia persist in water and become resistant to disinfectants commonly used for drinking water treatment. Giardiasis is a common gastrointestinal disease in developing countries, with a prevalence of 20 to 30% in children under 10 years (Khoury *et al*., 2016). All waterborne enteric pathogens can be deactivated by ultraviolet light, provided that are sufficiently exposed. Micro-organisms show different sensitivity to UV radiation: in general, bacterial spores and viruses have a relatively high resistance, while most bacteria are deactivated with lower UV doses (Timmermann *et al*., 2015).

Peru is one of the 20 countries with the most water in the world, however, between 7 and 8 million inhabitants do not have access to drinking water: new small towns and settlements do not have a water distribution system or sewerage. The city of Arequipa, located in southern Peru, has agriculture and livestock farming as its main activities. Most of the population dedicated to these activities does not have access to potable water, which increases health problems, especially gastrointestinal. Moreover, Arequipa is sunlit all year round which is currently inducing an increase in the use of this renewable energy source through photovoltaic panels. In Mexico, thermal studies of a solar still are being carried out by applying computational fluid dynamics (García-Chávez *et al*., 2020); industrial wastewater is also being treated using a solar heater, assisted by renewable energy (Gómez-Paredes, *et al*., 2020). Treatment for water disinfection with ultraviolet radiation is widely used in different places. The aim of the present work is to design and implement a system to treat water using ultraviolet (UV) radiation assisted with photovoltaic panels.

2 Materials and methods

2.1 Studied location

The study was carried out in the city of Arequipa - Peru (Coordinates: 15°51'36"S, 72°15'0"W), which has a population of 1 382 730 inhabitants. In its last evaluation from November 2018 to October 2019, the National Institute of Statistics and Informatics of Peru (INEI) reported that in rural areas 24.7% of the population did not have access to clean water through the public network. Among them, the highest percentage (15.4% of the population) consumed water directly from rivers, irrigations or springs and that 4.3% consumed water from wells (INEI, 2019). The experimental part was carried out in the field and at the Universidad Tecnológica de Perú.

Table 1. Electronic equipment.

Electronics	Input voltage	Output voltage	Fixed power
Inverter	12 Vdc	220 Vac	100 W
Regulator	36 Vdc	12 Vdc	300 W
Variator	12 Vdc	—	40 W
Photovoltaic panel	—	22.4 Vdc	120 W

Table 2. System components.

Component	Voltage	Current	Power
DC12V Pump	12 Vdc	1.6 A	19 W
UV System	220 Vac	0.08 A	16 W

2.2 Photovoltaic energy generation and control system

The following electronic equipment was used: 12V DC inverter, energy regulator or controller, inverter and photovoltaic panel (Intipower) (see Table 1). The components (see Table 2) were a DC12V pump (Model MDC-Pump -800, Naylamp) and a UV disinfection lamp (Model SEV-5345, Coronwater). All the components and equipment were purchased locally.

2.3 Design of the treatment system

The designed system is shown in Figure 1. It consists of a reservoir (a 500 L Rotoplas vase-type tank with antibacterial coating) for the storage of water coming from the source, which will later be pumped using a DC12V pump. The system conducts the water through a reusable sediment pre-filter ($\frac{1}{2}$", Junxiang / OEM), then through a 5-micron sediment filter (Pentair, WP-5 2.5" x10"), a 5-micron activated carbon filter (Pentair, EP-10 2.5" x10") and finally through the UV (254 nm) disinfection system. Finally, water is stored in a 250 L Rotoplas vase-type tank with antibacterial coating. The pump and the UV light system are fed using a photovoltaic panel, adapted and coupled to the system using locally sourced accessories. The tubes and unions of the entire system had a $\frac{1}{2}$" diameter.

2.4 Physicochemical and microbiological parameters

To obtain water at optimal conditions for human consumption, it is necessary to know the initial quality of the water before it is treated. This initial state will condition the processes to be implemented to attain compliance with the Mandatory Control Parameters (MCP) for water for human consumption required by the Peruvian General Health Directorate (DIGESA, 2011). According to DIGESA, the MCPs are the following: total coliforms, thermotolerant coliforms, color, turbidity, residual disinfectant and pH.

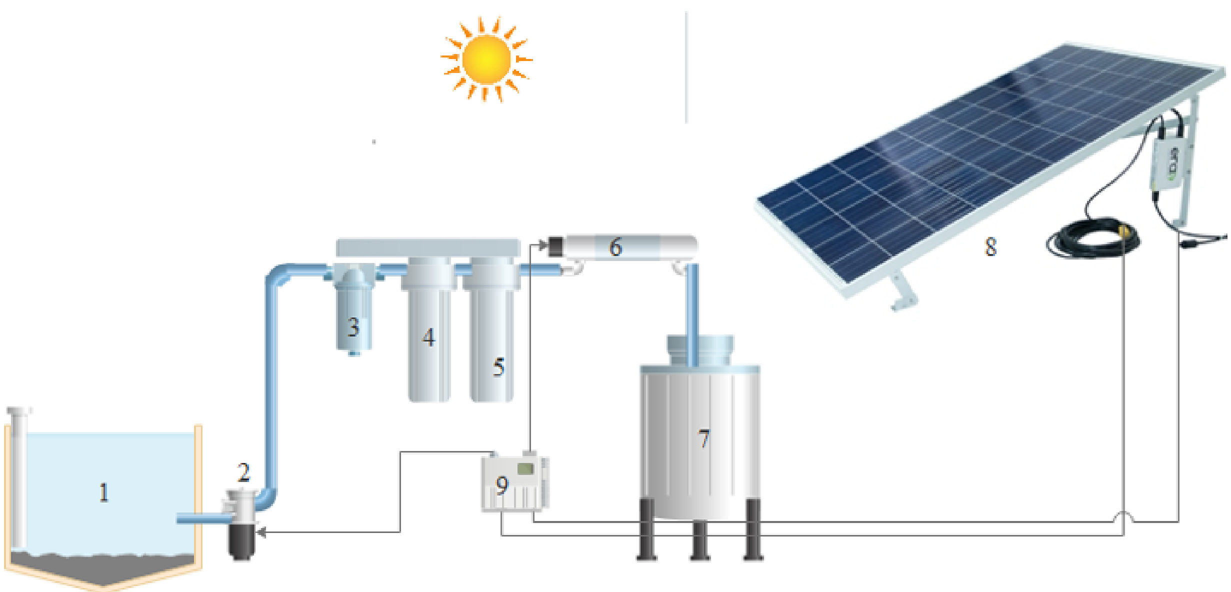

Fig. 1. Diagram of the water treatment system: 1) Raw water storage reservoir (1.16 x 0.76 m); 2) DC12V pump; 3) Sediment pre-filter; 4) Sediment filter; 5) Activated carbon filter; 6) UV light system; 7) Treated water storage tank (0.8 x 0.55 m); 8) Photovoltaic Panel (1.0 x 0.80 m) and 9) Control system and power generator.

Samples were taken and stored in hermetic and sterile 500 mL containers at 4°C. Then, they were transported to the laboratory for the physicochemical and microbiological analysis. For the microbiological analysis a 3M Petrifilm rehydratable plate method was used. All the reagents used were of analytical grade. The solutions were prepared with ultrapure quality water (18.2 MΩ) obtained with an EASY pure II equipment. The determinations were made using Genesys 150 UV-Vis spectrophotometer (Thermo Scientific), a portable turbidimeter (Hach), a HI2211-01 benchtop pH / mV meter (Hanna), a Pro-Plus professional multiparameter equipment (Ysi), an incubator (Binder), and a ME204 04-decimals analytical balance (Mettler Toledo).

3 Results and discussion

3.1 Evaluation of the photovoltaic energy generation and control system

Due to the energy requirements for the operation of the DC12V pump and the UV light disinfection system, a maximum power calculation was performed accounting for estimated losses and other environmental characteristics of the city of Arequipa. The city's solar potential is around 6.55 kWh/m^2/day: it is one of the cities where the energy performance of photovoltaic panels is higher and almost constant throughout the year, unlike most cities, which present seasonal variations (Espinoza *et al*., 2019). According to the Peruvian National Service for Meteorology and Hydrology (SENAMHI), the highest radiation in the city of Arequipa is attained at 11:49 a.m., with the highest intensity occurring from 9:30 a.m. to 2:00 p.m. Radiation is constant throughout the year in Arequipa, with an average of 5.5 kW generated per square meter per hour. (SENAMHI, 2020).

For the present study, a DC12V pump was used. It had an operating voltage of 5-12 V DC, a maximum current of 350 mA and a power consumption of 19 W. The ultraviolet light system (UV-C) had a power consumption of 16 W. For this reason, a 120 W photovoltaic panel was purchased, in order to satisfy the needs of the system even on a cloudy day. The system was fed only with a photovoltaic panel during the day. The remaining energy production was not stored, to avoid the high cost of battery systems.

3.2 Evaluation of the treatment system

The proposed system is shown in Figure 1. The first thing that was determined is the volume of water that had to be treated daily. For this, information on daily water requirements was collected. The volume was calculated based on the consumption of a 4-members family. The WHO estimates water consumption per inhabitant and per day (L/inhab/d) according to the level of service, access, needs and the effect on health. Water consumption for a low-level effect on the health of the inhabitant is 50 L/inhab/d (intermediate access). Considering that a family is made up of 04 people, the daily consumption per family is 200 L of water (OMS, 2013). Most of the people who live in the rural area of Arequipa have access to water from the Chili River, which has water throughout the whole year, increasing its flow in times of rainfall (December - March). The rural population has access to river water through irrigation channels and from the direct source, however, the water presents various types of pollutants such as wood, bags, other types of waste, and microbiological pollutants.

As seen in Figure 1, the system purifies water in line. The storage tank (500 L) has a stainless-steel mesh at the entrance in order to prevent the entry of polluting residues. The collected water goes through a natural sedimentation process allowing the suspended solids particles to settle at the bottom of the tank by gravity, allowing the filters to be cleaned from time to time in a quick and easy way.

Subsequently, the stored water passes through a low power $\frac{1}{2}$"-diameter centrifugal water pump, 12 VDC, with a threaded connection. The electric low consumption small pump was silent and designed to work continuously. Its internal motor was brushless, 19 W power, and allowed a water flow of up to 800 liters per hour. The water entered through a sediment pre-filter, which consisted of a 50-micron stainless steel mesh, allowing to retain particles. This pre-filter was easy to clean: it had a device that allowed to drain the retained particles, and thus extend the useful life of the other components.

Next, the water passed through sediment filters. Two types of filters could be used: a pleated cartridge made of resistant polyester, which is durable, washable and reusable, resistant to chemicals and bacteria, with the folds attached to a Polypropylene core for greater resistance, and a woven cartridge made from 100% woven polypropylene, with a high capacity for dirt retention. Both cartridges were highly effective in reducing sand, silt, sediments and oxide particles.

Table 3. Analyzed parameters before and after water treatment.

		Before			After		
Parameter	**Sample**	**Zone 1***	**Zone 2***	**Zone 3***	**Zone 1***	**Zone 2***	**Zone 3***
pH M.P.L. 6.50 -8.50	1	7.22	7.83	7.94	7.11	7.52	7.64
	2	8.23	8.27	8.09	7.95	7.8	7.47
	3	8	8.02	7.98	7.54	7.61	7.73
	4	7.79	7.96	7.91	7.71	7.57	7.42
	5	7.82	7.82	7.47	7.29	7.36	7.14
	6	8.01	8.04	8.37	7.93	7.49	7.88
Color: UTC Pt/Co scale M.P.L. 15	1	5.4	4.9	5.2	1.4	1.2	1.3
	2	6.1	5.7	6.3	1.5	1.4	1.6
	3	7.1	7.8	7.2	1.8	2	1.8
	4	5.3	5.3	5.2	1.3	1.3	1.3
	5	4.8	3.9	4.6	1.2	1	1.2
	6	6.4	6.8	6.1	1.6	1.7	1.5
Turbidity: NTU M.P.L. 5	1	3.01	3.15	3.24	0.75	0.79	0.81
	2	2.95	2.84	2.88	0.74	0.71	0.72
	3	3.08	3.21	3.15	0.77	0.8	0.79
	4	4.18	4.07	4.12	1.05	1.02	1.03
	5	2.69	2.72	2.65	0.67	0.68	0.66
	6	3.14	3.11	3.23	0.79	0.78	0.81
Conductivity uS/cm M.P.L. 1500	1	193.1	214	236	179.6	199	219.5
	2	202	197.7	200	187.9	183.9	186
	3	262	262	267	243.7	242.6	204.6
	4	220	232	220	204.6	215.8	204.6
	5	124	122.6	121.9	115.3	114	113.4
	6	135.1	135.8	134.1	125.6	126.3	127.7
Total Dissolved Solids mg/mL M.P.L. 1000	1	190	201	207	47	50	52
	2	175	175	173	44	46	42
	3	225	226	231	56	57	58
	4	191	200	190	48	50	48
	5	107	106	105	27	28	27
	6	117	117	116	29	30	29
Total Coliforms M.P.L. 0 UFC/100 mL	1	270	510	800	0	0	0
	2	310	450	1000	0	0	0
	3	280	370	693	0	0	0
	4	430	340	653	0	0	0
	5	380	370	813	0	0	0
	6	420	510	720	0	0	0
Thermotolerant Coliforms M.P.L. 0 UFC/100 mL	1	65	110	194	0	0	0
	2	74	108	250	0	0	0
	3	60	85	115	0	0	0
	4	96	68	123	0	0	0
	5	82	76	162	0	0	0
	6	93	104	132	0	0	0

M.P.L. Maximum Permissible Limits, (DIGESA, 2011).
*Zone 1: Cayma; Zone 2: Tiabaya; Zone 3: Uchumayo.

On the other side, the activated carbon filter was a cartridge made of high purity coconut shell carbon. This 5-micron filter effectively removed residual chlorine, organic chemicals, odor, taste, turbidity, sludge, suspended particles and other contaminants. It removed 85% of VOCs (volatile organic compounds). Both types of cartridges are commercialized locally, and their life span depends on their proper use and care, which is extended by using the pre-filter. For the present study, both 5-micron cartridges of 2.5" x 10" were purchased, as well as cartridge holders of the same dimensions.

For the disinfection, the water passed through the ultraviolet lamp. This system uses a unique and rapid method of disinfection of the water without the use of heat or chemicals to effectively destroy bacteria, viruses, molds and algae. UV light treatment is a widely recognized and proven method of water disinfection and has several advantages over others such as disinfection, chlorination, ozonation. The 253.7 nm UV-C light does not add anything to the water and does not generate hazardous products. It only adds energy in the form of ultraviolet radiation. Additionally, UV-C disinfection only requires a fraction of the contact times required by other disinfection methods. It is fast, efficient, effective, economical and respectful with the environment. The SEV-5345 water sterilizer is mainly used in the disinfection of domestic water, well water, residential water, or combined with other water systems, such as reverse osmosis system.

Preliminary studies used different UV-C radiation exposure times for the inactivation of total thermotolerant coliforms testing 4 seconds of exposure to UV-C radiation at an invariable dose of 0.00176 W/cm^2/s (Rossel Bernedo *et al*., 2020). In the present study, the hydraulic retention time (HRT) of the liquid passing through the reactor was 4 seconds; in the present study an inactivation time of 10 seconds was considered, with the objective of eliminating all the microbiological contaminants present.

3.3 Analysis of the physicochemical and microbiological parameters

Water samples were taken from the source in three different points. They were analyzed six times every seven days during January and February 2020. The samples were evaluated before and after the treatment. The water to be obtained had to be optimal for human consumption, according to the mandatory control parameters for water for human consumption (DIGESA, 2011). Table 3 shows the results of water samples before and after treatment. The evaluated MCPs are those required by DIGESA. To provide further results for the study, total dissolved solids and conductivity were also evaluated. The residual disinfectant MCP was not evaluated because the water does not contain chlorine since it was not submitted to a preliminary treatment. As seen in Table 3, the results obtained after treatment, using the proposed system, are under the maximum permissible limits required by DIGESA. The microbiological parameters were drastically reduced when exposed to UV-C light, which demonstrates the efficiency of this technology.

Conclusions

The obtained results show that it is possible to produce safe drinking water for human consumption from water taken from the source and comply with the mandatory control parameters established by DIGESA, using the proposed system.

The system was designed and implemented, as shown in Figure 1, using tanks for the storage of raw water and treated water, a DC12V pump, a pre-filter and filters for sediments, an activated carbon filter, a photovoltaic panel, a UV-C light lamp treatment system, a control system and a power generator. All of these items were sourced locally based on best price criteria. This means that a system of this type can be sourced and implemented and could prove its value in rural areas where drinking water is not available and that are currently facing health hazards coming from microorganisms present in untreated water. The use of UV-C light demonstrated being efficient for the removal of total and thermotolerant coliforms present in the water. Likewise, the applicability of photovoltaic panels as a power source for the UV-C system in areas where electricity is not available, was proven.

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