Automated Disinfection System for Polyethylene Terephthalate Bottles for Bacteria, Fungi, and Viruses Using UVC LED Camera

Gerson Orihuela, Esleiter Reyes, and Deyby Huamanchahua

1 Introduction

Faced with the global crisis, which is being experienced due to SARS-CoV-2. Health problems are a topic to be addressed worldwide, such as infectious diseases caused by bacteria, viruses, parasites, and fungi, practically by pathogenic microorganisms, which are contagious and are transmitted by inhalation of particles indirectly or directly (Bloom and Cadarette 2019). Likewise, the risks of contracting the virus have been increasing exponentially due to new sources of contagion such as markets, supermarkets, and crowded places, with the most frequent transmission of the virus through microdroplets or droplets that come off the nose (May 2021). These can be deposited on the surfaces of nearby materials, which are mostly handled and discarded, likewise, they can survive a couple of hours or up to several days depending on the material or residue (Quitral Q 2020).

Faced with this, all materials must have optimal handling from their production, consumption, and final disposal, so there must be a control and hygiene treatment for the comfort of people working in the recycling sector, to guarantee their health and well-being (Soliz Torres et al. 2020). The spread of the virus occurs most often in enclosed and poorly ventilated places, such as recycled waste treatment plants where recycled materials, many of them contaminated, accumulate to be treated for reintegration (Huayanay 2020). Considering that the main transmission mechanism is by contact and inhalation (Li et al. 2020), category C (UVC) ultraviolet light offers an efficient alternative in cleaning air and surfaces, which by eliminating said microbial particles reduces the probability of human contagion by the virus that circulates in an environment or space where there is contaminated recycled material accumulated with viruses and bacteria (Cervino et al. 2021; Manuel et al. 2020).

G. Orihuela · E. Reyes (✉) · D. Huamanchahua
Department of Mechatronics Engineering, Universidad Continental, Huancayo, Perú
e-mail: 48267395@continental.edu.pe

R. K Agarwal (ed.), *Recent Advances in Manufacturing Engineering and Processes*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-19-6841-9_2

According to studies and the ideal treatment with ultraviolet rays, it reduces the microbial load in contaminated material where UVC rays of the short wavelength of 200–280 nm are applied which generates a germicidal effect (Rattanakul and Oguma 2018; Kim et al. 2017; Hsu et al. 2021). UV rays possess a germicidal action that kills or neutralizes the action of viruses, bacteria, and other primitive microorganisms, so it is mainly used in the sterilization of surfaces and local medical, pharmaceutical, and food industry environments (Hsu et al. 2021; Raeiszadeh and Adeli 2020). The germicide lamp depends on the power and geometric shape considering the appropriate time of dose of UVC light emission, eliminating up to 99.9% of microorganisms (Nnadi et al. 2021; Dwivedi et al. 2021; Heilingloh et al. 2020).

UV irradiation has proven to be an effective physical means for the control of microorganisms, including viruses, with the UVC wavelength being most effective in practical application, followed by that of UVBs and finally that of UVA (Ou and Petersen 2008). The germicidal capacity against viruses lies in their ability to penetrate the viral structure, especially UVC and UVB (Nishisaka-Nonaka et al. 2018), which directly affect the genome preventing its replication and therefore leading to inactivation (Bono et al. 2021).

UVC treatment does not generate organoleptic variations, nor does it generate chemical residues and is effective in disinfecting the surfaces of products and materials (Raeiszadeh and Adeli 2020). Currently, UV light is used for the disinfection and sterilization of surgical products, cleaning of cell phones, purification of environments (Manuel et al. 2020; Rattanakul and Oguma 2018; Casini et al. 2019) process by which it performs to eliminate all forms of microbial life and bacteria (Kim et al. 2017; Dwivedi et al. 2021). It is also used in the disinfection of algae in ballast water based on a new treatment system with multiple ultraviolet waves in an approximate time interval of 20–30 s with a UV photocatalysis system (Lu et al. 2021).

Therefore, the objective of this article is to design a disinfection machine for recycled PET-type bottles using UVC radiation emitted by an LED camera, through an engineering development with the benefits of UV type C light, based on the mechatronic methodology of the Association of German Engineers (VDI 2206), composed of a mechanical, electrical-electronic and control system (Graessler and Hentze 2020), which makes it possible to sterilize recycled PET materials that accumulate in recycling plants for the process of insertion in society, since according to studies shows that 99.99% of viruses and bacteria are removed from the surface of materials and waste that are disposed of in urban areas and markets in general.

2 Methodology

The methodology used in the article is based on the VDI 2206 model. The methodology that represents the decomposition of the system is based on a V model for mechatronic systems that represents a logical sequence of activities composed of the left side the decomposition of the system and the right side the subsystems, which are constantly verified and validated (Graessler and Hentze 2020).

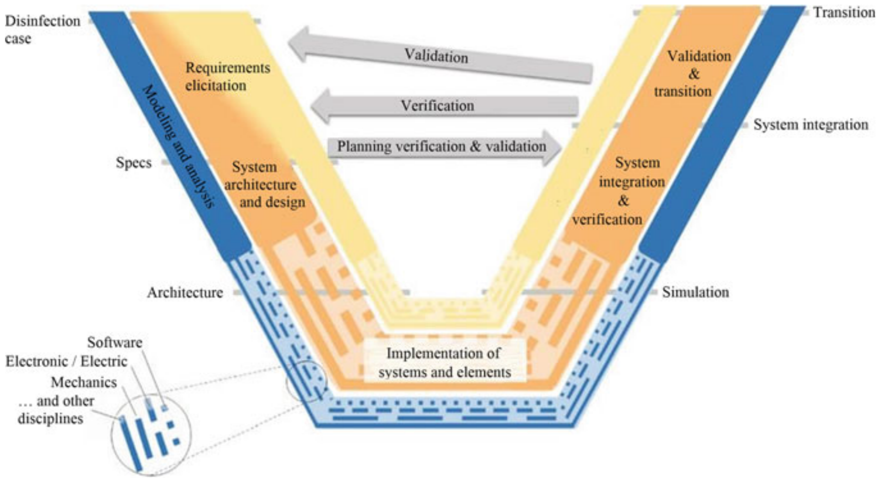

Fig. 1 Activities to be carried out in the VDI2206 structure

In Fig. 1, the approach of combining activities is shown, and the guideline suggests three main phases followed by a fourth that accompanies the other three: First, the *System design* that has an idea of the result between the influence that specifies the essential particularities logical and physical design motive, second the *Domain Specific Design* which establishes the need for further illustration through more detailed interpretations and calculations separately for each technical system, and the third phase is the *System Integration* which consists of evaluating the overall performance of the system when individual domains are integrated and the fourth is a cross-sectional *Modeling and Simulation* phase that creates and examines the qualities of the system with the support of structural models, tools, and computer-aided simulation instruments. The cycles of this project are the design of the LED camera and the functional simulation prototype. The prototype process includes 3D CAD software, Ladder programming, and the Factory IO integration system.

3 Materials

The mechanical system of the machine: Composed of the main motor (0.75 HP) that drives the conveyor belt (Siegling Transilon MT black E8/2 U0/V5H with $k1\% = 8$ N/mm) generating the transfer of recycled PET bottles toward the LED disinfection chamber of approximately three-square meters of area, after that the exit conveyor will be activated.

Electrical System–electronic machine: Composed of the main sensor and three secondary sensors (Diffuse Sensors) (Gutiérrez and Iturralde 2017). The objective of the main sensor is to detect the recycled PET-type material when it is inside the chamber, generating the stoppage of the conveyor belt and the start of the disinfection process. The ideal time to sanitize recycled bottles is 26 s (s) (Woo et al. 2019; Minamikawa 2008; Muramoto et al. 2008).

Machine control system: Employing a programmable logic controller (modular PLC) composed of programming lines in charge of giving instructions to the machine and storing them in its memory, represented by a control panel by pushbuttons, a liquid crystal display (LCD) for observing the count of disinfected materials, and light-emitting diodes (LEDs).

The prototype design of the UVC LED camera was developed in the Inventor program, to develop the virtual simulation of the Factory IO program with the use of PLC programming in the TIA Portal engineering system (Factory 2021; Download Inventor 2021; Software 2019). For the design, we must consider that when working with UV radiation with a range of 200–280 nm, the rays must be isolated, since produces a modification in DNA and this causes cancer (Muramoto et al. 2008; Buonanno et al. 2020). For this reason, strips of anti-ultraviolet ABS plastic sheet have been used to block the projection wave of the irradiation of ultraviolet rays at the beginning and the end of the disinfection chamber stroke (Rodríguez-Tobías et al. 2013).

Figure 2 shows the structural scheme of the prototype of the PET bottle disinfection system, whose structure is based on the process control system with the input and output signal. The vision system captures the input signal of the bottles to the conveyor belt with diffuse sensor inspection. The electronic system that turns on the feeding actuators of the PET bottles, the disinfection chamber that projects category C ultraviolet rays, and the removal of the disinfected material, generating a feedback signal or process concluded. The electromechanical system generates the mobilization of the conveyor belt, the illumination of the UVC LEDs, and the transport of the decontaminated PET bottles to their storage. The energy generates the impulse, the heat, the movement, the vibrations, and the light of the prototype.

4 Results

4.1 Disinfection Process Time

The maximum disinfection efficiency is 254 nm (nm), which depends on the time of 26 s (s) for the sterilization of the recycled PET bottles to be disinfected.

Figure 3 shows the disinfection chamber made up of four fundamental components; the first component is the chamber liner made of AISI 304 stainless steel from the American Iron and Steel Institute (Mundial 2021). The second component is the protection by strips of anti-ultraviolet ABS plastic sheet that blocks the projection wave of ultraviolet radiation (Rodríguez-Tobías et al. 2013). The third component is the LED type lights that project category C ultraviolet rays, and finally, the fourth component is the main stainless steel structure that ensures resistance, generates

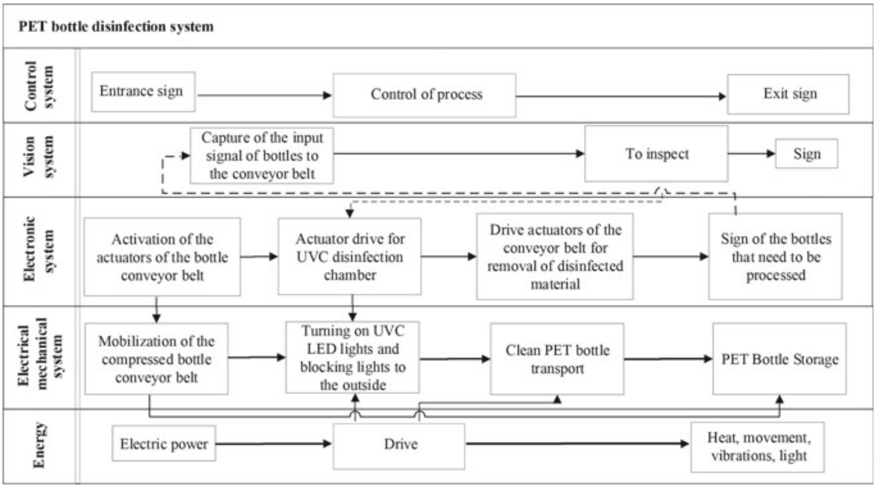

Fig. 2 Structural diagram of the disinfection system

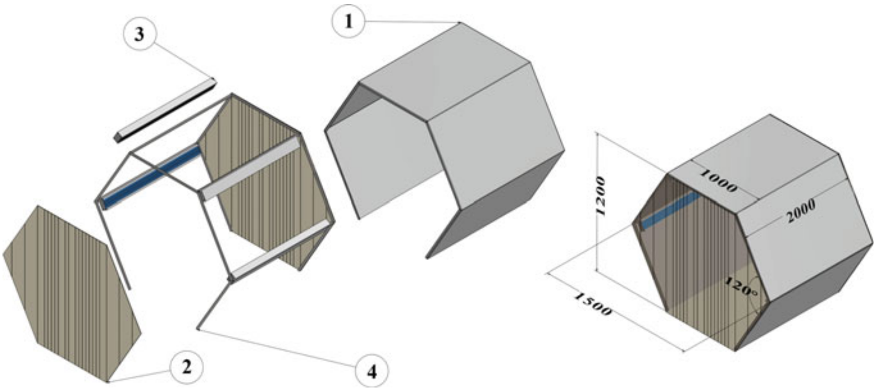

Fig. 3 LED camera that projects ultraviolet rays type C

the shape, and designs stability of the UVC LED camera, which has dimensions of 2000 cm long, 1200 cm high, and 1500 cm wide.

4.2 *Conveyor Belt*

It is based on the weight of the mass of 200 kg of PET bottles that will be transported approximately by the conveyor belt, and then the resistance of the conveyor belt to be used will be determined, consulting Eqs. 1 and 2. The maximum belt traction force (F_1) is calculated, which is the result of multiplying the tangential force (Fu) of 200 pounds equivalent to 1962 N by the smooth dry steel factor C_1 of 1.5 at an angle of 180° (Siegling 2016).

$$F_1 = Fu(C_1) \tag{1}$$

With the result of 2943 N, maximum traction of the belt is divided with the width of the belt (b_0) of one meter, it is compared with the maximum range factor of the type of tractor element of 2 that must have a conveyor belt multiplied by the tolerance $k_1\%$ of 8 N millimeters (N/mm) so that it works properly with the values provided by the technical manual (Siegling 2016).

$$F_1/b_0 \leq 2(k_1\%) \tag{2}$$

Therefore, with the result obtained of 2943 N/mm less than and equal to 16 N/mm, it is stated that the conveyor belt will perfectly resist the force exerted by the motor since the value is within the adequate working range as shown in Fig. 4.

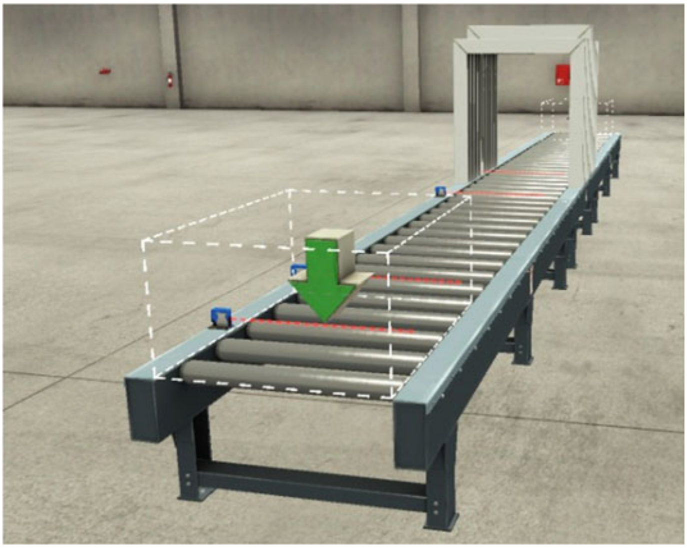

Fig. 4 Automated machine conveyor belt

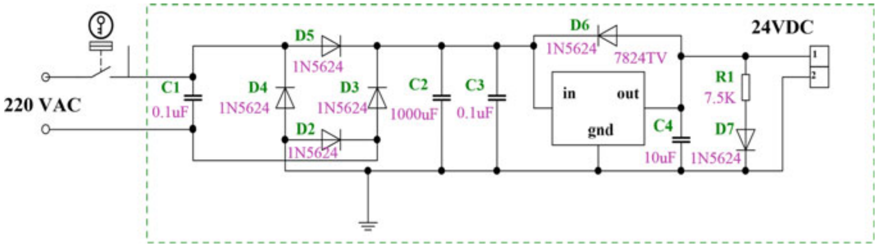

Fig. 5 Voltage regulation

4.3 Electronic Circuit and Programmable Logic Control Diagram

Figure 5 shows the electronic circuit that regulates the voltage from alternating current (VAC) of 220 V to a direct current voltage (VDC) of 24 V for the correct operation of the programmable logic controller.

Figure 6a shows the circuit diagram of the operation of the input and output PLC devices, and the outputs are seen as contactors KM1, KM2, and KM3, as well as the start and stop LEDs of the electronic receivers.

Figure 6b shows the power circuit, a part that generates the highest current consumption of the controller, this circuit oversees exciting the relays to activate the output devices, these work through semiconductor devices to control or modify the voltage or current of the machine.

Figure 6c shows the connection diagram of the input devices of the PLC that consists of a start, stop safety, emergency stop buttons, also inductive sensors, and control elements of the electronic diagram.

4.4 Ladder Programming Blocks

Figure 7a shows the segment with Ladder programming for the connection of Factory IO engineering programs with the TIA portal software.

Figure 7b shows the segment of the safety system and control drive of the automated machine.

Figure 8a shows the enumerator segment of the system, revealing the total amount of materials disinfected in a full working day.

Figure 8b shows the segment of the drive of the first conveyor belt that feeds the disinfection system, starting the count of material entering the C category UV LED chamber.

Figure 9a shows the segment of the drive of the ultraviolet led camera category C, with the estimated waiting time, while the material of the recycled PET bottles is

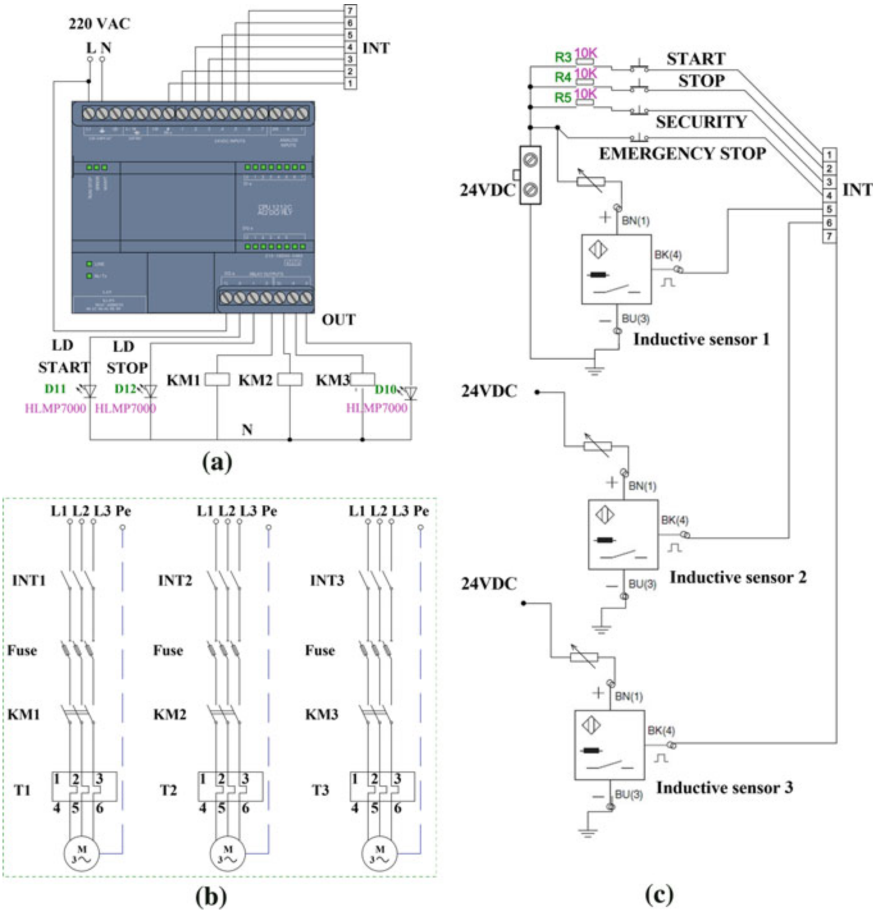

Fig. 6 **a** Programmable logic control, **b** power circuit and **c** PLC input connection diagram

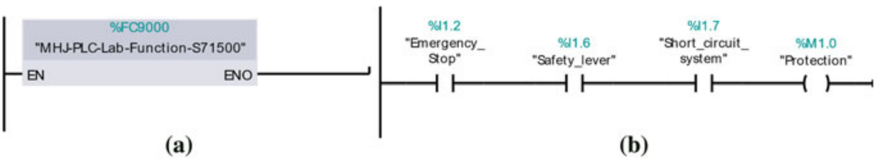

Fig. 7 **a** Connection factory IO–TIA portal and **b** security system

disinfected for 26 s, after which it generates the drive of the output conveyor belt for the warehouse of the recycling plant.

Figure 9b shows the segment of the outputs of the programmable logic controller that activates each drive component of the machine.

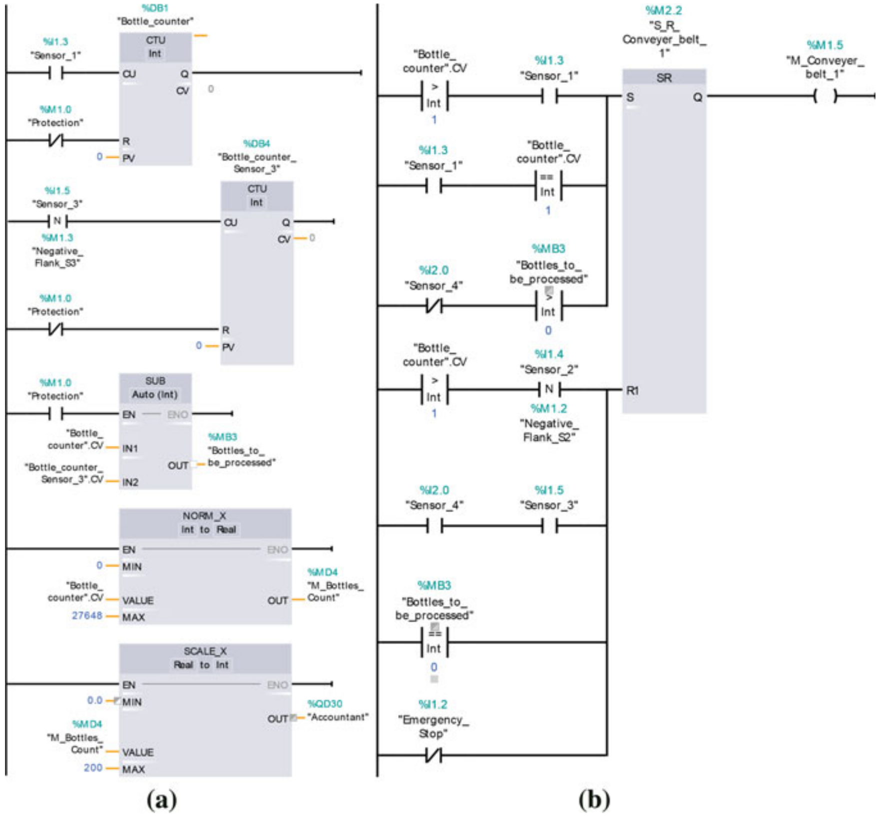

Fig. 8 **a** System counter and **b** drive of the conveyor belt and counter

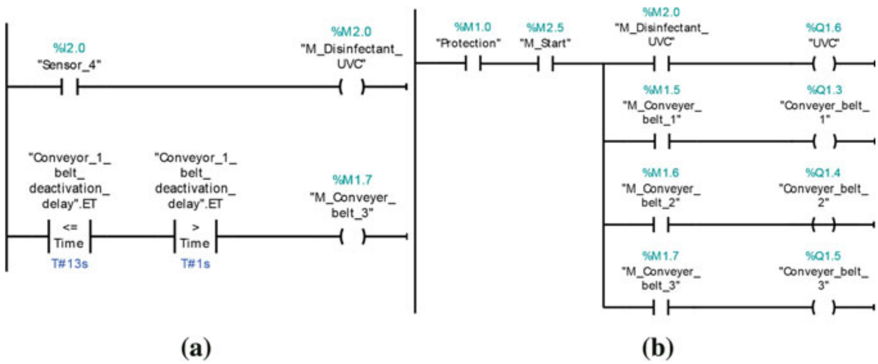

Fig. 9 **a** Disinfection and exit of the material and **b** component activation signal outputs

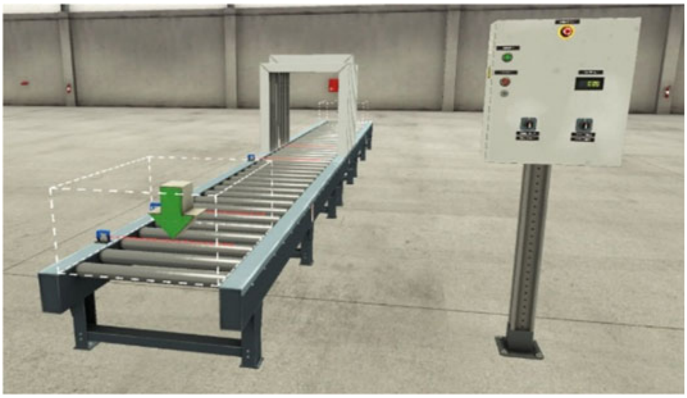

Fig. 10 Automated disinfection in factory IO of polyethylene terephthalate bottles for bacteria, fungi, and viruses; by UVC LED camera

4.5 *Automated PET Bottle Machine*

Figure 10 shows the final prototype of the automatic polyethylene terephthalate bottle disinfection machine that uses a 254 nm short-wave category C UV LED camera for the disinfection of bacteria, fungi, and viruses.

5 Discussion

SARS-CoV-2 is a highly variant and contagious virus due to its rapid transmission through droplets that settle on the surfaces of surrounding materials or by materials handled and discarded. Therefore, the disinfection system focuses on PET bottle recycling treatment plants with poor ventilation and closed environments for waste storage processes. These droplets remain impregnated on the surface of any material and at the same time in the process of transferring or displacing the contaminated material to reinsert the recycled polyethylene terephthalate material into society, the risk of contagion increases since the virus can survive for hours or days depending on the material where it resides.

That is why automated disinfection is important and necessary, with an LED camera that projects type C ultraviolet rays, sterilizes PET bottles against the threat of SARS-CoV-2 and highly contagious variant particles, thus efficiently eliminating impregnated viruses, generating security for the population of the recycling sector that plays a very important role in the collection and transformation of recycled material.

In this process, the recycled PET bottles enter through the conveyor belt to the UVC LED camera which has a memory program that applies 26 s to sterilize 99.99% of fungi, batteries, and viruses. With a short wavelength of 254 nm and an irradiation dose of 220 (J/m^2) Joule per square meter, the disinfected bottles are removed by the conveyor belt for their reinsertion process. This proposal is considered an emerging technology that agrees with the following studies (Rattanakul and Oguma 2018; Kim et al. 2017; Hsu et al. 2021; Raeiszadeh and Adeli 2020; Nnadi et al. 2021; Dwivedi et al. 2021) and (Heilingloh et al. 2020) which consists of control surfaces. The recycled PET bottles, at the illumination of the wave range of 200–280 nm, it is confirmed that there is greater sterilization with the emissions of 254 nm.

6 Conclusion

In conclusion, it is highlighted that the machine works with ideal automated treatment, with category C short-wave UV radiation, and this reduces the microbial load found on the surface of polyethylene terephthalate materials in the recycling plant. This UVC disinfection strategy is highly effective in eradicating up to 99.99% of microorganisms and viruses; this method being an alternative to help disinfect surfaces in the current pandemic, so this research shows how to safely disinfect the surface to be treated.

Implement the proposal both in different recycling and disinfection sectors, which will allow its effectiveness to be verified, and also to adapt and improve both the model and the proposed methodology and tools.

Finally, this research will serve for the development and improvement of similar machines; since its purpose is that viruses, fungi, and bacteria do not remain on the surfaces of the materials that are processed for their reintegration into our society.

References

Bloom, D.E., Cadarette, D.: Infectious Disease threats in the twenty-first century: strengthening the global response. Front. Immunol. **10**, 549 (2019). https://doi.org/10.3389/fimmu.2019.00549

Bono, N., Ponti, F., Punta, C., Candiani, G.: Effect of UV irradiation and TiO_2-photocatalysis on airborne bacteria and viruses: an overview. Mater. (basel) **14**(5), 1075 (2021)

Buonanno, M., Welch, D., Shuryak, I., Brenner, D.J.: Far-UVC light efficiently and safely inactivate airborne human coronaviruses. Res. Square (2020)

Casini, B., et al.: Evaluation of an ultraviolet C (UVC) light-emitting device for disinfection of high touch surfaces in hospital critical areas. Int. J. Environ. Res. Public Health **16**(19), 3572 (2019)

Cervino, C.O., Almandoz, J.C., Mignone, M., Irusta, A., Leiton, G.: The use of UV-C radiation for disinfection in the face of the COVID-19 pandemic: new portable UV-C disinfection system, UNIMORON-Desinfector© (2021)

Download Inventor 2022: *Autodesk.com*, [Online]. Available in: https://latinoamerica.autodesk.com/products/inventor/free-trial. Last accessed 06 Apr 2021

Dwivedi, V. et al.: Rapid and efficient inactivation of SARS-CoV-2 from surfaces using UVC light-emitting diode device (2021)

Factory I/O—Next-Gen PLC Training. *Factoryio.com.* [Online]. Available in: https://factoryio.com/download-archive/. Last accessed 15 Apr 2021

Graessler, I., Hentze, J.: The new V-Model of VDI 2206 and its validation. Autom. **68**(5), 312–324 (2020)

Gutiérrez, M., Iturralde, S.: Basic fundamentals of instrumentation and control, First Edition, Editorial EUPSE, Ecuador (2017)

Heilingloh, C.S., et al.: Susceptibility of SARS-CoV-2 to UV irradiation. Am. J. Infect. Control, **48**(10), 1273–1275 (2020)

Hsu, T.C., et al.: Perspectives on UVC LED: Its progress and application. Photonics **8**(6), 196 (2021)

Huayanay, L.: Airborne transmission in closed spaces of SARS-Cov-2. An. Fac. Med. **81**(3), 342–347 (2020)

Kim, D.K., Kim, S.J., Kang, D.H.: Bactericidal effect of 266 to 279 nm wavelength UVC-LEDs for inactivation of Gram-positive and Gram-negative foodborne pathogenic bacteria and yeasts. Food Res. Int. **97**, 280–287 (2017)

Li, Q., et al.: Early transmission dynamics in Wuhan, China, of novel Coronavirus-infected pneumonia. N. Engl. J. Med. **382**(13), 1199–1207 (2020)

Lu, Z., Wang, Y., Zhang, S., Zhang, K., Shi, Y., Meng, C.: Multi-wave UV-photocatalysis system (UVA+UVC+VUV/Cu-N-TiO2) for efficient inactivation of microorganisms in ballast water. Mater. Express **11**(9), 1608–1614 (2021)

M. Manuel et al., "Development of a UV-C air sterilizer for the control of airborne transmission of COVID-19", Innovación y Desarrollo Tecnológico y Social, vol. 2, num. 2, pp. 167–203, 2020.

Material Mundial: AISI 304 Stainless Steel Technical Sheet, Properties, Density, Hardness. *Materialmundial.com*, [Online]. Available: https://www.materialmundial.com/acero-inoxidable-ss-astm-sae-aisi-304-ficha-tecnica/. Last accessed 15 Sept 2021

May, U.: The risks—know them—avoid them. Scpns.com. [Online]. Available in: http://www.scpns.com/wp-content/uploads/2020/06/The-Risks-Know-Them-Avoid-Them.pdf. Last accessed 20 Oct 2021

Minamikawa, T. et al.: Inactivation of SARS-CoV-2 by deep ultraviolet light-emitting diode: a review. Jpn. J. Appl. Phys., **2008** (2021)

Muramoto, Y., Kimura, M., Kondo, A.: Verification of inactivation effect of deep ultraviolet LEDs on bacteria and viruses, and consideration of effective irradiation methods. Jpn. J. Appl. Phys. **2008** (2021)

Nishisaka-Nonaka, R., et al.: Irradiation by ultraviolet light-emitting diodes inactivate influenza a virus by inhibiting replication and transcription of viral RNA in host cells. J. Photochem. Photobiol. B **189**, 193–200 (2018)

Nnadi, D.B.N., Araoye, T.O., Egoigwe, S.V., Vincent, D.A.: Application of robotics UV-light device in averting the spread of Coronavirus. Res Square (2021)

Ou, Y., Petersen, P.M.: Application of ultraviolet light sources for in vivo disinfection. Jpn. J. Appl. Phys. (2008), **60**(10), 100501, (2021)

Raeiszadeh, M., Adeli, B.: A critical review on ultraviolet disinfection systems against COVID-19 outbreak: applicability, validation, and safety considerations. ACS Photonics **7**(11), 2941–2951 (2020)

Rattanakul, S., Oguma, K.: Inactivation kinetics and efficiencies of UV-LEDs against Pseudomonas aeruginosa, Legionella pneumophila, and surrogate microorganisms. Water Res. **130**, 31–37 (2018)

Rodríguez-Tobías, H., Morales, G., Rodríguez-Fernández, O., Acuña, P.: Mechanical and UV-shielding properties ofin situsynthesized poly(acrylonitrile-butadiene-styrene)/zinc oxide nanocomposites. J. Appl. Polym. Sci. **127**(6), 4708–4718 (2013)

Siegling, F.: Conveyor belts, and processing, conveyor belt calculation. 2016. Retrieved from: https://docplayer.es/11410149-Calculo-de-la-banda-transportadora.html. Last accessed 20 Oct 2021

"Software": *Siemens.com*, [Online]. Available in: https://new.siemens.com/mx/es/productos/automatizacion/industry-software/automation-software/tia-portal/software.html. Last accessed 27 Aug 2019

Soliz Torres, M.F., Durango Cordero, J.S., Yépez Fuentes, M.A., Solano Peláez, J.L.: The right to health in the recycling trade: community actions against COVID-19. Quito, EC: Universidad

Andina Simón Bolívar, Ecuador Headquarters/VLIR-UOS/Zero Waste Campaign, Ecological Action/Global Alliance for Alternatives to Waste Incineration (2020)
Woo, H., et al.: Efficacy of inactivation of human enteroviruses by dual-wavelength germicidal ultraviolet (UV-C) light-emitting diodes (LEDs). Water (basel) **11**(6), 1–1131 (2019)
Quitral Q, Y.A.: Libraries in the face of the COVID-19 pandemic: fundamentals and actions in Latin America. Bibl. Univ., (2020). https://doi.org/10.22201/dgb.0187750xp.0.0.992