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Green energy powered - vapor, thermal and UV light assisted disinfection technology

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A B S T R A C T

Infectious diseases are responsible for an immense global burden of disease that impacts public health systems and economies worldwide. The rapid increase in the use of protective items has introduced an urge for their reuse and safe dumping to minimize the threat of disease transmission through cross-contamination. The existing disinfection processes are mostly powered with non-renewable energy sources and focus on single disinfecting technology that limits their installation to in-house applications and reduces the degree of disinfection, respectively. Thus there is a need to develop new strategies and innovations powered by renewable energy sources that enhance the degree of disinfection of daily-use objects and curtail the spread of the infection through cross-contamination. The present study reports a smart automatic technology called "REACTIV-FIT". The technology is developed as an exercise bike with a disinfection chamber that efficiently kills viruses, bacteria, and other germs/pathogens. The current developed technology is equipped with three disinfecting protocols in one system. The system is powered by renewable solar energy and utilizes the mechanical energy during exercise into electrical energy using a generator-based mechanism. The portable smart automatic disinfection box embedded in the bike utilizes the synergetic effect of ultraviolet (UV), thermal, and vapor treatment for sterilizing objects. During vapor treatment, the continuous supply of the sterilizing solution is maintained through a storage tank attached to the outer body of the box and can be easily refilled. In the final step of the disinfecting protocol, the objects are exposed to UV-A light having a peak wavelength of 365–370 nm. The automatic disinfection process is powered by renewable solar and mechanical energy during cycling. The developed technology can be installed in schools, offices, and industries, and its renewable energy-powered feature offers installation in parks, tourist places, streets, remote areas, etc.

1. Introduction

The wide spread of infectious diseases can result in health emergencies like a pandemic. An infectious disease can be caused by viruses, bacteria, pathogens, etc., which spread through transmission from an infected person, or a contaminated object to a susceptible host. Infectious diseases are responsible for an immense global burden of disease that impacts public health systems and economies worldwide [1,2]. According to WHO, the best solution to curtail its widespread is by adopting preventive measures at the early stage [1–3]. Thus there is an extended need to develop new strategies and innovations to disinfect daily-use objects and curtail the spread of the infection through cross-contamination [1–2]. While breathing and talking, the resultant aerosol dispersion and infected surfaces/objects are the prime transmission routes. The quality of the air we breathe and the cleanliness of the surfaces we touch profoundly affect our health and well-being. We're all at

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risk of contracting and spreading infection, especially in busy public areas. Under these circumstances, as we prepare to step outside for work, daily use objects continue to pose the threat of transmitting the infection. Thus, to prevent the spread, it is recommended to use a mask and gloves to avoid catching the infection, and even disinfecting daily use objects has become essential. Moreover, the rapid increase in the use of protective items has introduced an urge for its reuse and safe dumping to minimize the threat of virus transmission. The market is flooded with various disinfecting technology. Table 1 lists the few disinfecting technologies reported in the literature and existing in the market. These technologies mainly rely on a single disinfecting method, such as thermal, ultraviolet (UV) light treatment, or sterilization [4–10]. Thus, incorporating a single disinfecting technology reduces the degree of disinfection. Moreover, the existing disinfection technology relies on renewable sources for power. The energy dependency hampers their usage in remote and tourist places. Thus there is a need to develop new strategies and innovations to increase the degree of disinfection of daily-use objects, and technology should be powered with green renewable energy sources.

In the present work, we report a smart automatic technology called "REACTIV-FIT". The technology uses three different disinfecting methods (thermal, sterilizing vapor, and ultraviolet (UV)-A light) that sequentially treat the objects and ensures a higher degree of disinfection. Secondly, running this disinfecting unit with renewable solar and mechanical energy generated during physical exercise. Even complete technology is developed as an exercise bike to encourage people to work out and avoid the common health problem associated with obesity and overweight [18]. Implementing current reported technology will also promote clean, environmentally friendly, and health factors.

Table 1
Various disinfection technologies are reported in the literature and exist in the market.

Technology	Description	Reference
Schwartz A et al.	Decontamination and reuse of N95 respirators with hydrogen peroxide vapor to address worldwide personal protective equipment shortages during the SARS-CoV-2 (COVID-19) pandemic	[11]
CleanDefense Clean box	UV treatment-based hygiene product. The technology is based on UV treatment for disinfecting point-of-use protective products that are not feasible to clean by a solution-based process.	[12]
Central Salt & Marine Chemicals Research Institute	A special self-disinfecting mask that can give enhanced protection against the virus	[13]
University of Arizona	A washable mask that would kill 99 % of bacteria and viruses	[14]
Maya sticker	3D printed unique film called 'Maya sticker' can be attached to a face mask to increase its protective capabilities	[15]
Disinfecting device	A sanitizing system uses ultraviolet light within a housing having an interior chamber	[16]
Methods and compositions for cleaning and disinfecting surfaces	Relates to the problem of cleaning and disinfecting unclean surfaces that are contaminated, typically with bacteria, viruses, yeast, and molds.	[17]
Green energy powered - vapour, thermal and UV-C light assisted disinfection technology	• Disinfecting unit utilizing synergetic effect of UV-A, Thermal and vapor treatment • Supported with on renewable energy • Exercise cycle	Present work

2. Methods and materials

Arduino Uno *R*3 microcontroller kit, infrared (IR) sensors, Temperature sensor (DS18B20), Solar panel, and 8-channel relay was purchased from Voltaat Qatar. UV-A light tube with peak wavelength centered at 365–370 nm and power 18 W and Dynamo motor generator was purchased from Amazon.

Fig. 1 shows the wired connections of the various component that governs the autonomous vapor, thermal and UV light-based sequential disinfection of the objects. IR sensor is connected at pin 3 and triggers the motor connected at pin 2 on/off through a relay switch for touchless opening/closing of the disinfecting unit gate. The disinfecting process is triggered by the IR sensor connected at ping 0. Once the disinfecting process is triggered, the water pump connected at pin 10 through the relay switch is turned on and fills the disinfecting solution. After that, the vapor treatment is triggered by connection at pin 5 through the relay switch followed by powering the vapor treatment connected at pin 4 through the relay switch. After the vapor treatment, the objects were sequentially treated by the thermal and UV light connected at pin 8 and 9 through a relay switch, respectively. During the thermal treatment, the overheating of the disinfecting chamber is continuously monitored and controlled by the temperature sensor connected at pin 11. The status of the disinfecting process, such as the current running disinfecting process and time left, are displayed on the LCD screen connected at pins A5 and A4 using master and slave configuration. The two Arduino are powered with a USB connection through the power bank.

3. Results and discussion

The current developed technology is equipped with three disinfecting protocols in one system. This prototype combines the benefits of a thermal, chemical, and UV-A-enabled sequential disinfecting unit and a cardio workout, utilizing eco-friendly sources. The equipment is constructed to encourage the disinfection of objects by harnessing power through green energy sources and creating awareness about physical activities. The various technological features embedded in the prototype are discussed below.

3.1. Disinfection unit

The automatic disinfection unit utilizes the synergetic effect of UV-A, thermal and sterilizing vapors to disinfect masks, gloves, and personal objects. The schematic representation of the disinfecting prototype is shown in Fig. 2. The disinfecting unit consists of two chambers. The bottom chamber contains the vapor sterilizing setup, thermal treatment setup, and electrical connections. The upper half contains a UV-A treatment setup and arrangement for the systematic placement of objects to be disinfected.

3.1.1. Vapor disinfection

The sterilizing solution is evaporated from the bottom of the box and disinfects objects placed in the upper chamber. The heating element attached to the vapor disinfecting box evaporates the sterilizing solution, and the fan attached to the box ensures the uniform upward movement of the vapors. The tank attached to the outer body of the disinfection unit stores the sterilizing solution, and the motor inside the tank ensures the continuous supply of the solution to the sterilizing box during each disinfection cycle.

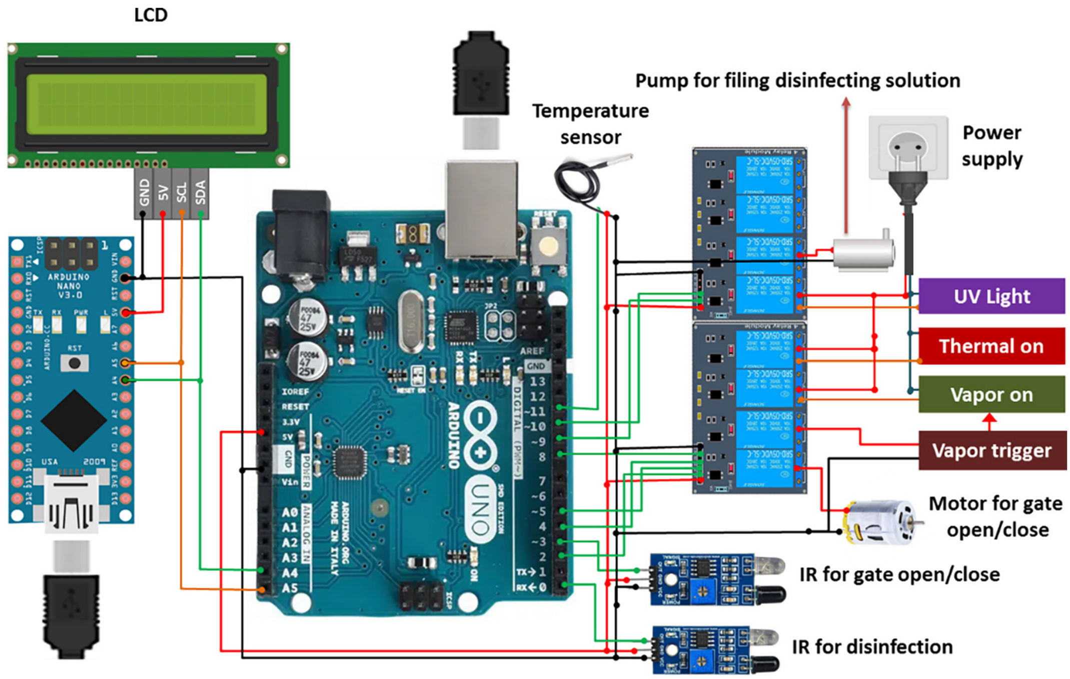

Fig. 1. Schematic illustrating the wire connection diagram of the developed vapor, thermal and UV light based disinfecting technology.

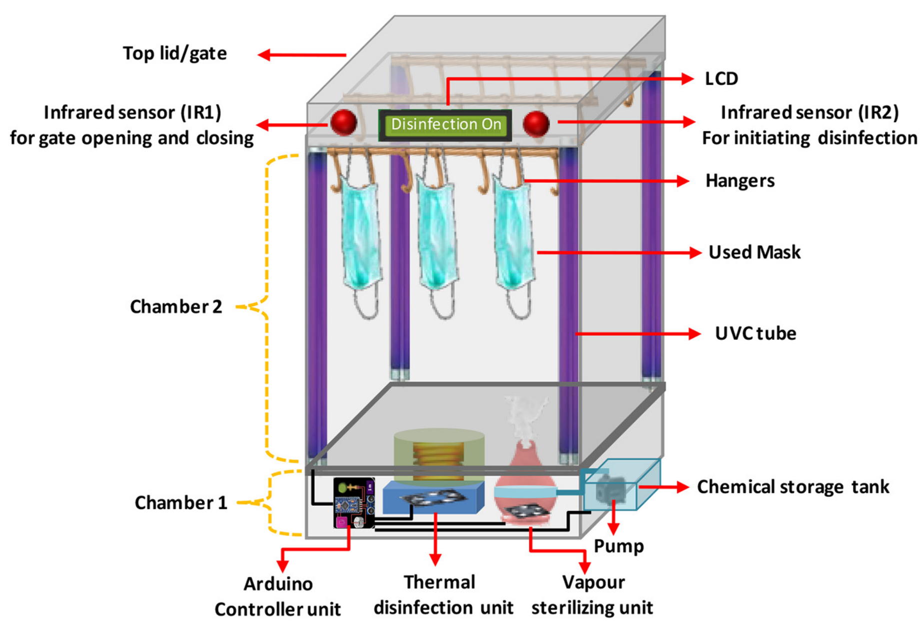

Fig. 2. Schematic representation of the autonomus disinfection box prototype embedded with sequential thermal, vapor and UV light disinfecting technologies.

The solution storage tank on the disinfecting unit's outer body enables sterilizing solution to refill easily.

3.1.2. Thermal disinfection

The thermal treatment is based on the heat generated from the induction coil. The fan attached to the coil forces the hot air toward the objects. The temperature inside the chamber is continuously monitored by the temperature sensor placed inside the box and helps maintain a suitable temperature range during thermal treatment. The thermal disinfection works following the feedback of the temperature sensor placed inside the box. During the complete thermal treatment cycle, when the temperature exceeds the disinfecting range, the temperature sensor signals to turn off the heating coil and again turn it on if it reaches below the disinfecting range.

3.1.3. UV-A light disinfection

The UV-A disinfection is based on the exposure of the objects to the UV light having a peak wavelength centered at 365–370 nm. The exposure time is kept long enough to ensure effective disinfection. The disinfecting box comprises four UV-A tubes attached to the box's four corners (see Fig. 2). The arrangement of UV-A tubes in a specified manner ensures the maximum surface coverage of the objects placed inside the box. Treatment duration is kept sufficient enough to sanitize and disinfect the surfaces properly.

3.1.4. Programming

The disinfecting box is equipped with an Arduino-programmed system to govern the automatic working and control the exposure time of different disinfecting processes. The program also controls an LCD attached to the top of the box to continuously display the various ongoing protocols and temperatures inside the box. The program for the sequential disinfection and autonumus working of the prototype has been given in the supplementary information.

3.2. Automatic working of disinfecting unit

Here is a step-by-step functioning of the smart automatic disinfecting box. The disinfecting unit remains on standby when no action is taken and displays the temperature inside the box. The working vedio of the developed technology has been provided as supplementary information.

Step I: The top lid/gate of the disinfecting box can be automatically opened/closed by interrupting the signal from the infrared sensor (IR1) attached to the front panel of the unit. The opening and closing of the gate are assisted by a single IR sensor that works on the alternate opening/closing logic.

Step II: First time when IR1 sensor senses the signal, it opens the top lid, and the user can place/hang objects to be disinfected, such as masks, gloves, etc., next to each other. The LCD displays "Gate Opening" and the temperature inside the box.

Step III: After placing the objects inside the box the second time, when the IR1 sensor senses the signal, it closes the top lid of the disinfecting box. The LCD displays "Gate Closing" and the temperature inside the box.

Step IV: The user can start the disinfecting process by interrupting the infrared signal from the second IR sensor (IR2) on the front panel. Once the user initiates the disinfection process, the gate will be closed for the entire disinfection process. The gate doesn't open even when the user tries to open it by interrupting the signal from the IR1 sensor, which is responsible for gate opening/closing. This feature is incorporated to give extra safety during the disinfection process. First, the objects placed inside the box are disinfected from the sterilizing solution vapors. Before the start of this step, the motor placed in the storage tank runs for a short period and fills the sterilizing box kept inside the chamber. After this, the vapor sterilizing unit is powered on for a while to sterilize the objects placed in the chamber and then turned off. The LCD displays "Vapor Disinfection On" and the temperature inside the box. The vapor disinfection is followed by the thermal disinfection process using a hot induction coil as a heating source. The fan attached below the coil forces the hot air toward the objects. The thermal disinfection works per the feedback of the temperature sensor placed inside the box. During the complete thermal treatment cycle, when the temperature exceeds the disinfecting range, the temperature sensor gives a signal to turn off the heating coil and again turn on if the temperature reaches below the disinfecting range. The LCD displays "Thermal Disinfection On" and the temperature inside the box. The UV-A disinfection process immediately follows the thermal treatment. The UV-A light inside the box is turned on for a while. The LCD displays "UV Disinfection On" and the temperature inside the box.

Step V: Once the disinfection process is complete, the disinfecting unit again goes into its initial standby mode. The sterilized objects can be removed from the chamber by interrupting the signal from the IR1 sensor, which intern opens the gate of disinfecting unit.

Fig. 3 shows the various component embedded in the disinfecting unit. The hanger is designed to place the object and hang the mask and gloves. The disinfecting chamber has UV-A, thermal, and vapor treatment. The image of the prototype exhibiting the UV-A disinfection is shown in Fig. 3 (right).

3.3. Powering disinfection unit with green energy

The possible architecture of the disinfection unit assembly that utilizes the electrical energy generated from the exercise cycle and solar radiation as the potential power inputs is shown in Fig. 4. The benefits of powering with renewable solar energy sources also bring limitations, such as inconsistent sunlight during the day and low power generation due to dust accumulation and clouds. Further, the mechanical work cannot be enough to power the technology for multiple treatments. Thus, to minimize the limitations of green energy sources, the reported technology is embedded with the battery that stores the generated power and will help install the technology in remote areas. Moreover, the technology can also be directly powered with the power supply for its uninterrupted in-house application. The cycling device consists of a seat with a pedal arrangement similar to an indoor bicycle. The seat can be moved back or front easily to get an optimum position for pedaling.

The general components embedded in the proposed prototype which are required to build the final equipment include:

i. Exercise Bike: A front-mounted wheel with a channel, with the generator pulley at 5 cm diameter.
ii. Power generator (dynamo): The dynamo will be connected to the fly-wheel using a belt, as shown in Fig. 5. The power generated from the dynamo will be stored in the battery.
iii. Rechargeable Battery: Lead-acid auto battery.
iv. DC/DC converters: A Set of DC/DC converters: the first one 12/24 V DC (1.5 kW) keeps (during PM = 0 mode) constant DC Bus voltage, therefore directly safeguarding proper operations of the 24 V DC loads. Both 12/24 V DC converters are constructed based on the same boost structure. The converter is automatically turned off only if the input voltage exceeds its minimum value.
v. Solar panel: a solar panel size 200 × 200 cm2 (0.3 kWh) will be connected to the battery.

The experiments were conducted using an improved stationary bike which can generate power by using an electric generator (dynamo) and can save the electrical energy in a battery (DC) to run a disinfection unit. A generator was connected to the exercise bike machine to start the electric power production. The mechanisms adopted are such that the generator is attached to a stationary bicycle in which the circular rotations of the front wheel rotate the wires coils against the poles of the magnets placed inside the generator. The faster the pedaling, the more electricity is generated. It was also explored that at a speed of 25 kph, it was possible to achieve 200 W for shorter periods. These results show that the existing battery banks can be powered by human/mechanical energy when harnessed. The power generation from the exercise bike is usually low; to compensate, a solar panel will be connected for energy alterations.

On top of the bike, a solar panel will be connected of size 200 × 200 cm^2 (0.3 kWh). The Solar panel will be installed on top of the whole setup to provide the required energy to run the disinfection protocol. It will provide shade and protect the disinfecting unit from any external hazards. The PV module generates DC electrical energy when exposed to sunlight. A front protective glass secures the module. The solar panel provides continuous energy to the battery to ensure the uninterrupted operations of the attached disinfection unit. The voltage and current ratings of the panel were calculated, and the functioning of the PV is tested

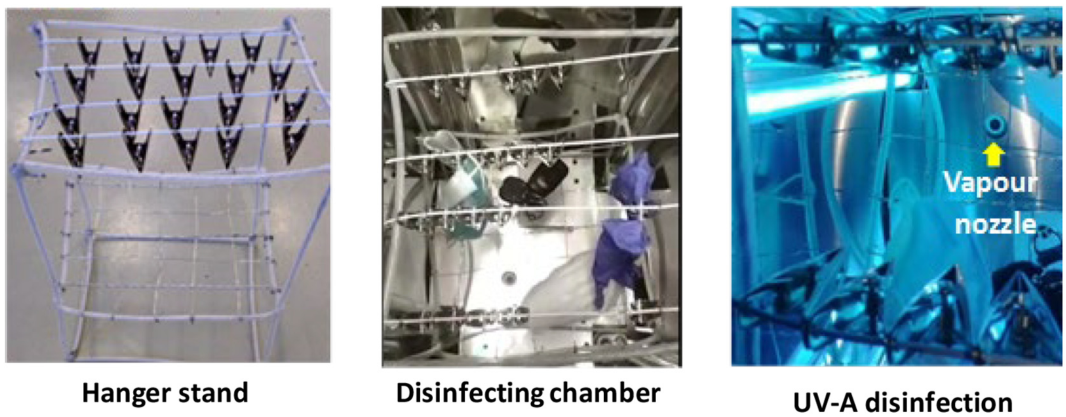

Fig. 3. Various components incorporated in the disinfecting unit including hanger (left), disinfecting chamber for placing objects (center) and UV light treatment (right).

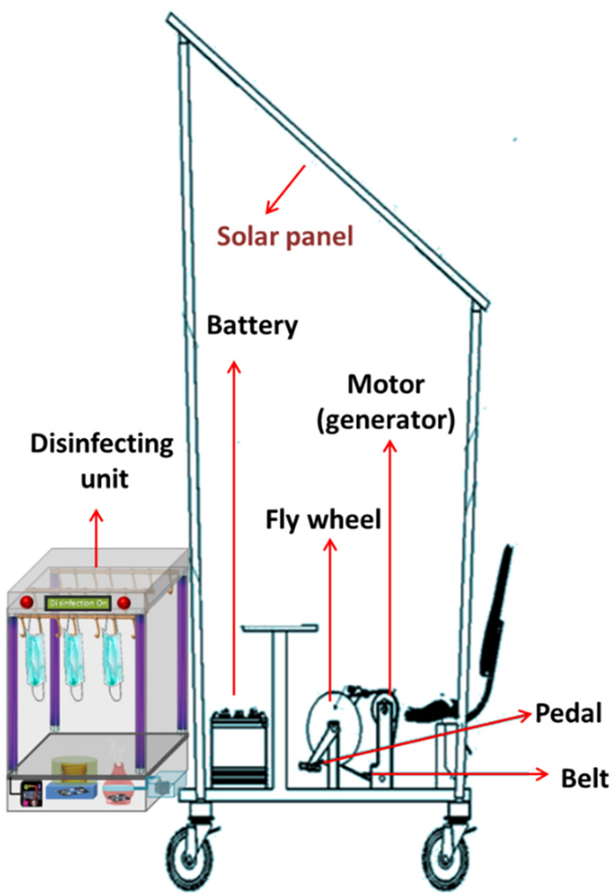

Fig. 4. Schematic representing the fusion of disinfecting technology with the exercise bike for powering with green energy sources via mechanical energy generated during exercise and solar panel attached on the roof of the bike. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Dynamo/flywheel connections.

to ensure normal operation even in unexpected conditions of high current or voltage produced in the panels. Necessary precautions have been taken to account for any accidental high-voltage generation. The fuse size and controls are used accordingly. The PV module can function accurately under high temperatures up to 85 °C and relative humidity ranging from 45 % to 95 %. The tilt angle of the PV module is selected to generate the maximum output power when it faces the sun directly. Also, the output is tested to be adequate even when the irradiance is low during winter. The module frame is attached to the mounting using corrosion-proof screws. The module can withstand a pressure of 2400 Pa in case of local winds. The clamps and supports ensure that the module withstands the load. High torque is applied to fix the module steadily. The module frame and mounting rack are grounded aptly.

Fig. 6a explains the working principle of the disinfecting unit by using power from three different sources: the dynamo (pedaling), solar panel, and direct power. The dynamo is connected to the flywheel of the bicycle using a belt and works as a power generator that can charge the rechargeable battery. The generator is attached to the flywheel with the help of a belt, which spins at a speed of around 1500 rpm. The solar cell also charges the battery simultaneously, as shown in Fig. 6a. A rechargeable battery setup is installed which is connected to the dynamo so that the energy generated from the dynamo can be saved. The mechanical energy of the pedaling is converted into electrical energy and is stored in the battery. The battery used for storing the energy is placed in an insulated and ventilated battery case specifically designed for this purpose. The battery used has low maintenance and high performance. A PV charge controller is used to protect the battery. The nuts, bolt screws, and fasteners used in the equipment construc-

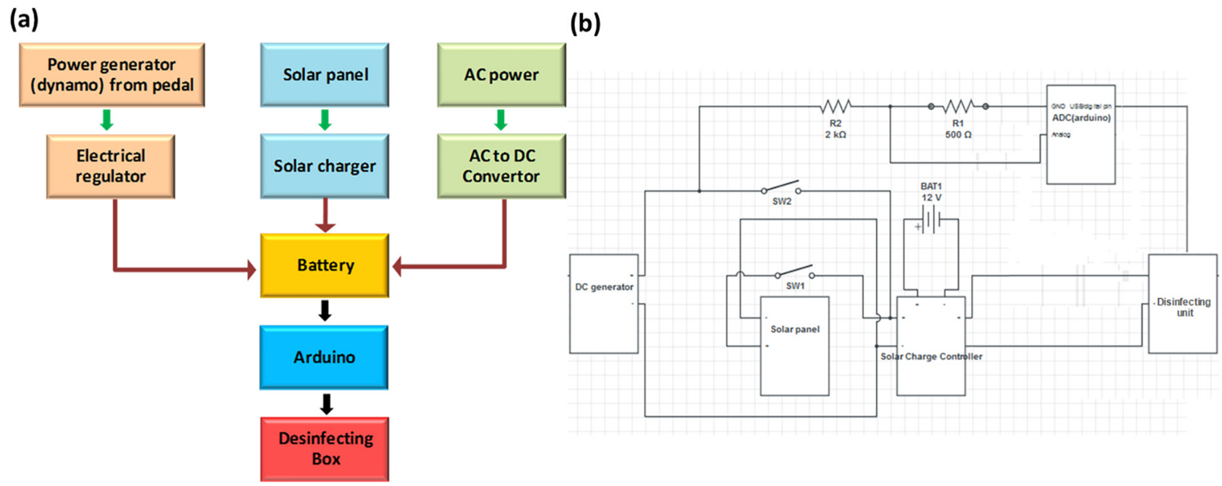

Fig. 6. (a) Flowchart of disinfection unit working based on power supply, human and solar power. (b) The circuit involved in powering the disinfecting unit.

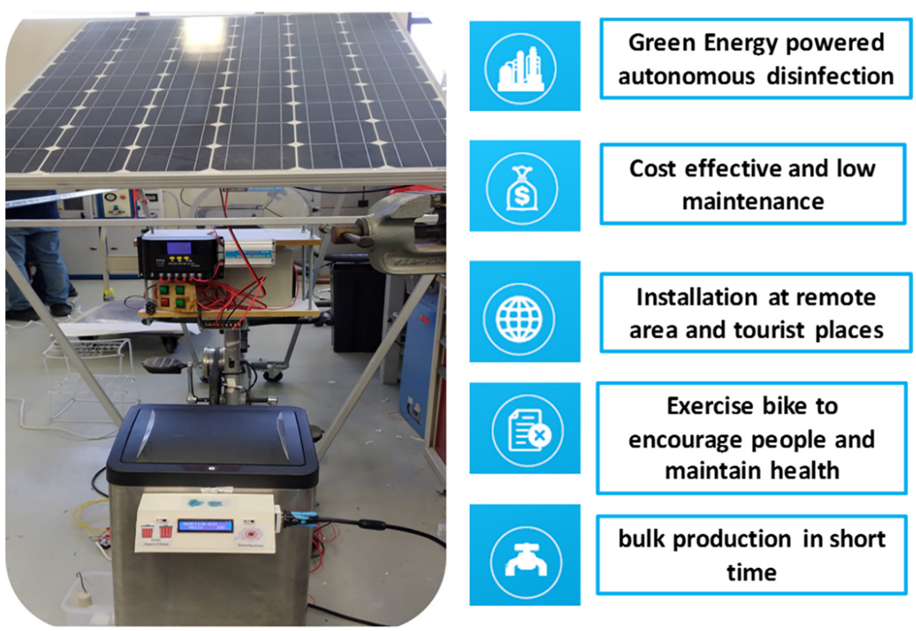

Fig. 7. Photograph of the developed disinfecting unit powered with green energy sources and key advantages. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tion are tightened with the right torque. User safety has been considered with the utmost care, and the precautions have been planned and executed accordingly. Fig. 6b shows the circuit diagram for powering the disinfection unit.

Fig. 7 shows the photograph of the developed disinfecting unit powered by green energy sources. For a leading cyclist, it was easy to generate more than 400 W/day, which is approximately more than half a horsepower if the workout session is prolonged for an hour or further at a maximum stretch. Still, for an average person, even somebody in good shape, the maximum amount of electricity generated was only around 50 to 150 W. It will easily allow a disinfecting unit to run for approximately an hour. Let's assume that the average exercise equipment is used for 5 h a day, 365 days a year. Based on capacities that were made in deliberated fitness clubs, we calculated that: For 1 year (295 working days), the total electrical energy consumption was about 4800 kWh, and it could be utilized for the disinfection process.

Further, with the increasing consciousness about hygiene and fitness, leading a healthy lifestyle has become a significant factor. With its built-in technologies, this equipment provides the opportunity to experience scientific advancements in an extremely simple demonstration. The heightened demand for exercise bikes is because of the increasing health consciousness among the global population. As people know, cycling is responsible for the isotonic exercise of the body and helps improve stamina, stimulate heart rate, and burn down body fat. Fig. 8 shows the potential beneficiaries of the developed technology. We strongly believe this technology will be highly useful in encouraging people to maintain hygiene, a safe environment, and health. The developed technology can be installed in schools, offices, industries, and its renewable

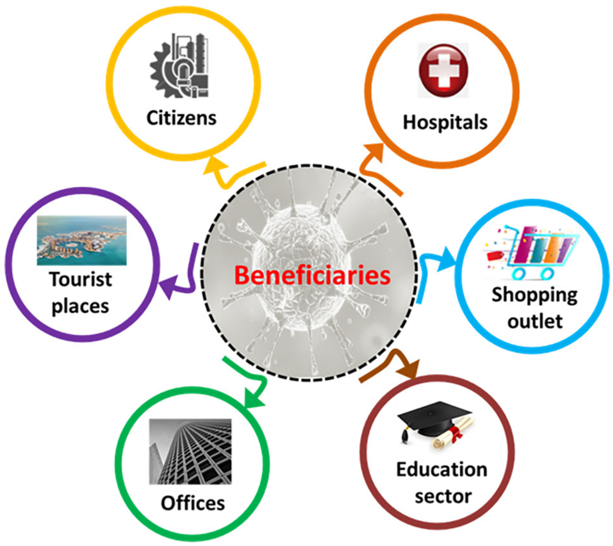

Fig. 8. Potential application area of the developed technology.

energy-powered feature offers installation in parks, tourist places, streets, remote areas, etc.

4. Conclusion

In summary, a high degree of disinfecting unit powered by green energy was successfully developed. The prototype combines the benefits of thermal, chemical, and UV-enabled sequential disinfecting with a workout, utilizing eco-friendly sources. The touchless opening and closing of the equipment and initializing the disinfection were implemented. Simple modifications in the program can control the time of each disinfection. The overheating of the disinfecting chamber during thermal treatment was protected using a temperature sensor. The developed prototype exhibited a high degree of disinfection. The developed technology showcased the simple design to harness renewable energy for physical activity using an exercise bike and solar energy, which is used to power disinfecting. We strongly believe this equipment solves the problem related to the issue of disinfecting personal protective wearables and objects and increasing adverse health issues. The skills used in this art make the product more susceptible to incorporating modifications and changes relatively based on the specific requirements or users. Implementing the above technology also promotes the clean, environmentally friendly, and healthy factor with application in areas such as parks, tourist places, streets, buildings, remote places, etc.

CRediT authorship contribution statement

Kishor Kumar Sadasivuni: Methodology, Conceptualization, Supervision, Writing – review & editing, Funding acquisition. **Muni Raj Maurya:** Methodology. **Mohammad Talal Houkan:** Methodology, Formal analysis. **John-John Cabibihan:** Methodology, Formal analysis, Conceptualization, Supervision, Writing – review & editing. **Mithra Geetha:** Validation. **Somaya Al-Maadeed:** Validation. **Nazreen Che Roslan:** Data curation. **Dania Adila Ahmad Ruzaidi:** Data curation. **Mohd Muzamir Mahat:** Data curation.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matpr.2023.02.245.

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