AMETHYST: Advanced Microbial Eradication Through High-Intensity Yielding Sterilization Technology - A Multipurpose Decontamination Chamber Using 405 nm HINS Light

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Abstract. This paper presents the design and concept of a multipurpose decontamination chamber named AMETHYST (Advanced Microbial Eradication Through High-intensity Yielding Sterilization Technology), which serves as a cabinet for object decontamination and, with its outward-opening doors, can also effectively decontaminate an entire room. The development of this chamber is driven by the need for efficient and versatile decontamination solutions, particularly in response to the COVID-19 pandemic. The focus of this paper is to discuss various UV light techniques considered during the design process and the ultimate selection of 405 nm High Intensity Narrow Spectrum (HINS) light as the preferred wavelength. The proposed concept offers a flexible, cost-effective, and sustainable solution for achieving high levels of decontamination in both object and room environments.

Keywords: 405 nm · Decontamination · Experimental Validation

1 Introduction

The recent COVID-19 pandemic has brought to light the significance of hygiene and decontamination in public health, particularly in underserved areas where access to basic sanitation and healthcare services is limited.

2 Importance of Decontamination Chambers in Underserved Areas

The significance of hygiene and decontamination in preventing the spread of infectious diseases has been emphasized during the COVID-19 pandemic, especially in underserved regions. In these areas, access to safe water, sanitation, and hygiene (WASH) services is often limited. The integration of decontamination chambers for the disinfection of spaces and items can be instrumental in these settings.

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- **Reducing Cross-Contamination:** Decontamination chambers can mitigate the risk of cross-contamination in healthcare facilities by disinfecting medical equipment, personal protective equipment, and other items before they are transported from one area to another.
- **Enhanced Cleaning Protocols:** Complementing traditional cleaning methods, decontamination chambers ensure that microorganisms are effectively eliminated.
- **Safety and Efficiency:** The automation of decontamination chambers, often utilizing light technologies or vaporized hydrogen peroxide, offers both safety and efficiency.
- **Public Confidence:** Visible decontamination efforts, such as decontamination chambers, can bolster public confidence in the safety of public spaces.
- **Adaptability:** Decontamination chambers can be adapted for various settings and purposes.
- **Resource Conservation:** In resource-limited settings, decontaminating personal protective equipment is critical for resource conservation.
- **Preventing Future Outbreaks:** By ensuring spaces and items are decontaminated, chambers can contain the current pandemic and prevent future outbreaks.

It is imperative that decontamination chambers be integrated as part of a broader public health strategy, coupled with improvements in WASH services. These measures should be reinforced by education and behavior change campaigns to underscore the importance of hygiene and decontamination in preventing the spread of infectious diseases.

2.1 The Use of 405 nm Light in Decontamination Chambers

Traditional decontamination chambers often employ ultraviolet C (UV-C) light for disinfection. While effective, UV-C light can be harmful to humans and materials, posing a risk of skin burns and eye injuries. Moreover, repeated exposure to UV-C light can lead to the degradation of materials such as plastics.

An alternative and safer approach is the use of 405 nm light for decontamination. This wavelength, which is in the visible spectrum, has been shown to be effective in inactivating a wide range of microorganisms, including bacteria and viruses. The advantages of using 405 nm light include:

- **Safety:** Unlike UV-C light, 405 nm light is safe for human exposure and does not cause harm to the skin or eyes.
- **Material Compatibility:** 405 nm light does not degrade materials such as plastics and textiles, which makes it suitable for decontaminating a wider range of items.
- **Effectiveness:** Studies have shown that 405 nm light can effectively inactivate microorganisms through a different mechanism than UV-C, and is particularly effective against bacteria, including antibiotic-resistant strains.

- **Continuous Decontamination:** Because 405 nm light is safe for human exposure, it can be used for continuous decontamination in occupied spaces, whereas UV-C light can only be used when spaces are unoccupied.

The use of 405 nm light in decontamination chambers provides a safer and often more effective alternative to traditional UV-C light, making it particularly valuable in settings such as healthcare facilities, schools, and public transportation, where safety and material compatibility are paramount.

2.2 Background and Motivation

Studies have shown that 405 nm light can effectively inactivate microorganisms and coronaviruses. Examples include [1–5]. Based on this there is a strong motivation to further develop innovative decontamination chambers using the 405 nm wavelength, which is much safer to use in occupied spaces than the more common UV-C light, with the only penalty being that it takes more time for treatment.

2.3 Research Objectives

The main objectives of this research are to design and evaluate a multipurpose decontamination chamber using 405 nm UV light, focusing on its efficacy in eradicating microbial contaminants on objects and room surfaces.

2.4 Significance of the Study

This study is significant as it offers a new and innovative approach to decontamination that is flexible, cost-effective, and environmentally friendly. It also addresses a critical public health issue.

3 Background

3.1 Decontamination Methods and Challenges

Decontamination is essential in ensuring the cleanliness and safety of environments, particularly in healthcare settings. However, traditional decontamination methods have faced numerous challenges that have highlighted the need for more efficient and effective solutions.

Traditional Decontamination Methods. Traditional decontamination methods primarily involve the use of chemical disinfectants and manual cleaning. Chemical disinfectants, such as hydrogen peroxide, peracetic acid, and hypochlorous acid, are often used to clean surfaces. Additionally, some approaches involve coating surfaces with antimicrobial agents like copper or silver to create self-disinfecting surfaces.

Challenges with Traditional Methods. One of the significant challenges with traditional methods is the suboptimal cleaning and disinfection practices in hospitals. This is often due to various personnel issues and failure to follow the manufacturer's recommendations for disinfectant use. Additionally, some disinfectants lack antimicrobial activity against healthcare-associated pathogens, affecting the efficacy of disinfection practices.

Moreover, manual cleaning is labor-intensive and can be inconsistent, leading to areas being inadequately decontaminated. The human factor in manual cleaning also introduces the possibility of error, and the cleaning process itself can sometimes contribute to the spread of contaminants.

405 nm Light for Decontamination. 405 nm visible light, which is in the range of violet-blue visible light (380–500 nm), has been shown to have germicidal properties and is considered as an alternative to germicidal ultraviolet C (UVC) irradiation for disinfection, especially in environments occupied by humans. The 405 nm light has demonstrated the ability to reduce bacteria, surgical site infections, and inactivate certain viruses. This is believed to be due to the absorption of light by photosensitizers such as porphyrins, which leads to the release of reactive oxygen species (ROS). ROS are known to cause damage to essential biomolecules such as proteins, lipids, and nucleic acids in bacteria, fungi, and viruses, and can also lead to the loss of cell membrane permeability through lipid oxidation.

Although 405 nm light is less germicidal than UVC, it has been shown to have the potential to inactivate pathogenic bacteria such as Listeria spp. and Clostridium spp., as well as fungal species such as Saccharomyces spp. and Candida spp. Furthermore, 405 nm light has been shown to inactivate viruses such as feline calcivirus (FCV), viral hemorrhagic septicemia virus (VHSV), and murine norovirus-1, especially when used in conjunction with media suspensions containing photosensitizers.

In a specific study [6], it was shown that 405 nm light could inactivate SARS-CoV-2 and influenza A H1N1 viruses without the use of photosensitizers, making it directly relevant to clinical environments. The study employed a commercially available visible light disinfection system that ensured the irradiance used was safe and practically achievable in a clinical setting. The study supports the potential use of 405 nm light as a tool for continuous decontamination of respiratory pathogens such as SARS-CoV-2 and influenza A viruses.

3.2 Comparative Analysis Table

Table 1 provides a comparative analysis of three different decontamination methods: AMETHYST, UV Disinfectant Lights, and Traditional Cleaning Methods. It evaluates them across multiple criteria such as their primary goal, mechanism, safety, effectiveness, and areas of application to offer a comprehensive view of their relative advantages and drawbacks.

Table 1. Comparative Analysis Table

Feature	AMETHYST	UV Disinfectant Lights	Traditional Cleaning Methods
Primary Goal	Multipurpose Decontamination	Surface and Air Decontamination	Surface Cleaning
Mechanism	405 nm HINS Light	UV-C Light	Chemical Disinfectants
Human Safety	High	Low (risk of skin and eye damage)	Varies (depends on chemicals)
Material Safety	High (No material degradation)	Low (degrades materials)	Medium (chemical residues)
Effectiveness	High	High	Medium to High
Time Required	More Time Required	Faster	Labor-Intensive, Varies
Areas of Application	Objects and Rooms	Unoccupied Spaces	Surfaces

3.3 Strengths and Weaknesses

3.3.1 AMETHYST

Strengths: Highly effective, safe for humans, versatile, enhances public confidence.

Weaknesses: Takes more time for treatment, relatively new technology.

3.3.2 UV Disinfectant Lights

Strengths: Fast, effective against a broad range of microorganisms.

Weaknesses: Harmful to humans, degrades materials, specific use-cases.

3.3.3 Traditional Cleaning Methods

Strengths: Proven effectiveness, widely available.

Weaknesses: Labor-intensive, chemical residues, inconsistent cleaning, doesn't boost public confidence.

3.4 Underserved Areas

In underserved areas, the challenges of decontamination are often exacerbated. Limited resources and infrastructure mean that access to effective decontamination agents and equipment is restricted. Additionally, there is often a lack of trained personnel to carry out decontamination procedures effectively. The combination of these factors makes infection control in underserved areas particularly challenging. Table 2 summarise some potential solutions.

Table 2. Comparative Analysis of Decontamination Solutions

Solution	Technology	Scope	Suitability for Underserved Areas
CERTEK CMDC	Chemical Decontamination	N95 Masks	High Mobility
She et al. UV-C System	UV-C Light	Surfaces	Low Cost, High Flexibility
Biosept Home UV-C	UV-C Light	Hospital Surfaces	Portable, Non-Toxic
Lifx Clean	HEV Blue Light	Air & Surfaces	Dual-Purpose, Safe

3.5 Other Solutions for Underserved Areas

The CERTEK Mobile Decontamination Chamber (CMDC) presents an innovative approach, particularly advantageous for underserved areas. The CMDC is a transportable decontamination chamber manufactured in one-trip shipping containers. It is capable of decontaminating thousands of N95 compatible masks in one cycle. The chamber is equipped with double doors, LED lighting, and an electrical panel. These mobile decontamination chambers are especially beneficial in areas with limited decontamination infrastructure, as they can be easily transported and deployed [7].

She et al. explore the use of UV-C light as a disinfectant for bacteria and viruses, aiming to develop a cost-effective and portable solution particularly advantageous for low-resource settings. The authors design and validate a lightweight UV-C disinfection system, constructed from readily available components such as a plastic bin and a standard UV-C light bulb. The interior of the system is coated with reflective chrome paint to intensify the UV-C exposure. The efficacy of the system is validated using Bacillus cereus, a gram-positive bacteria known for its resilience to harsh conditions including UV exposure. Analytical calculations and experimental validations suggest that a 3-minute exposure can achieve a UV-C dose exceeding 500 mJ/cm^2, which is well beyond the guidelines for bacterial and viral decontamination. The model they provide also allows for rapid adaptation of the system design to accommodate different light sources or exposure times. This solution is particularly relevant for disaster relief scenarios or healthcare systems in underserved areas where access to large, commercial decontamination systems is limited [8].

The study by Tamires dos Santos and Lívia Furquim de Castro shows that the Biosept Home UV-C device effectively decontaminates hospital surfaces using UV-C light. Notably, its portable nature makes it an advantageous solution for underserved areas that may lack comprehensive decontamination infrastructure. In testing, the device demonstrated complete bacterial inactivation and reduced microbial colonies on hospital surfaces. The Biosept Home UV-C offers a promising, portable, and non-toxic alternative for ensuring hospital cleanliness in resource-limited settings [9].

The Lifx Clean is a smart lightbulb that has been developed to not only provide lighting but also kill bacteria in its vicinity. The bulb utilizes high-energy visible (HEV) blue light of around 405 nm wavelength.

For underserved areas, this technology offers a dual-purpose solution. The Lifx Clean provides both lighting and a degree of microbial disinfection, all integrated into a single household device. Its safety profile makes it more user-friendly compared to other disinfecting technologies like UV light, which can be harmful if used improperly. Though not a complete solution for all types of pathogens, in resource-limited settings where multi-functional devices can be particularly beneficial, Lifx Clean presents a viable option for enhancing cleanliness [10].

4 Design and Development of AMETHYST

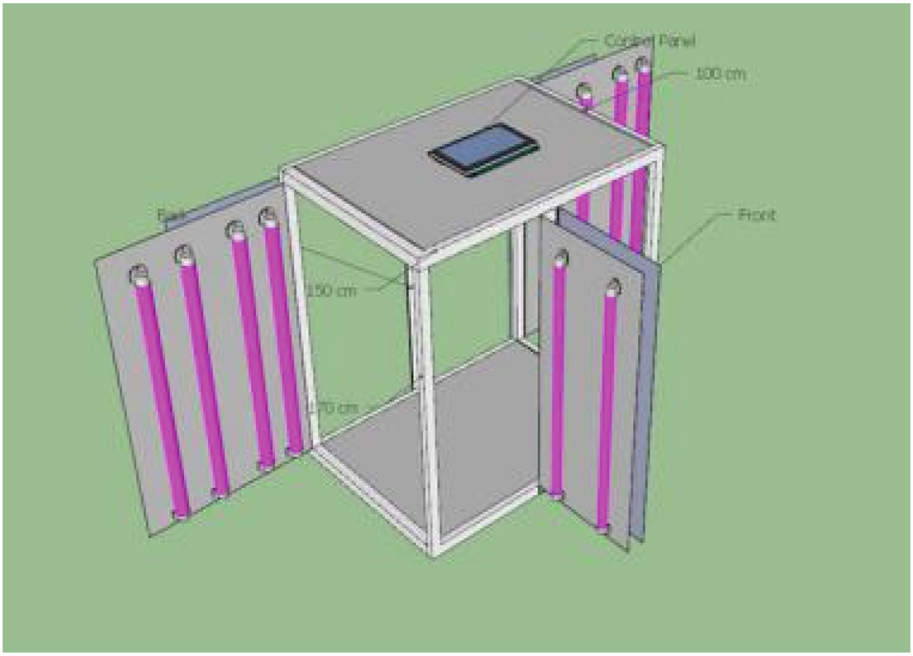

Fig. 1. Initial design

The primary design, as depicted in Fig. 1, conceptualizes the doors as capable of opening outwards entirely, thus ensuring every corner of the room is covered. In essence, the doors offer a seamless, all-encompassing coverage. When closed any items inside the chamber will be disinfected thoroughly.

4.1 System Overview and Components

The AMETHYST system utilizes high-intensity violet light, specifically at a wavelength of approximately 405 nm, to effectively eradicate microbial contaminants. The working principle involves the use of high-power light-emitting diodes

(LEDs) that emit violet light. These LEDs are strategically placed within the decontamination chamber to ensure uniform coverage of the targeted area and within the chamber (Fig. 2 shows room disinfection mode).

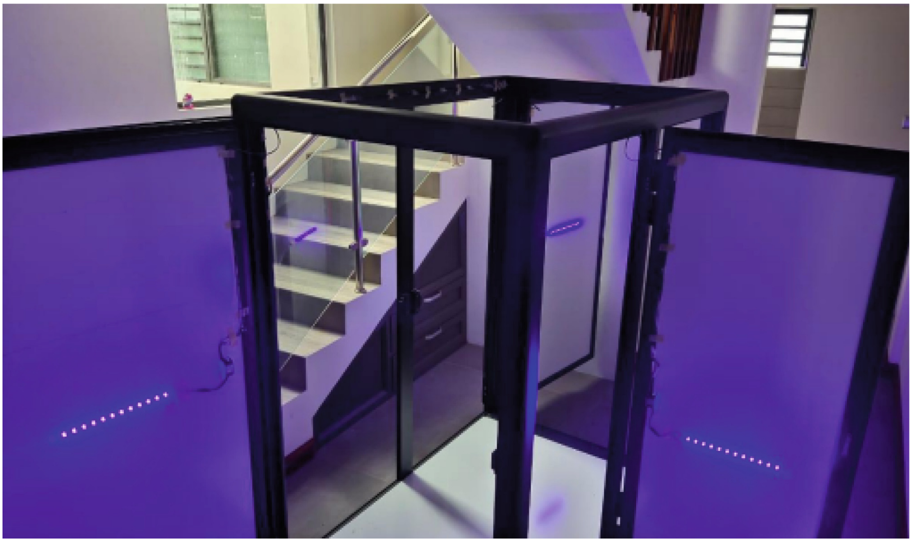

Fig. 2. Room mode

4.2 Violet Light Source and High-Intensity LED Technology

The light source comprises multiple disinfection lights, which use high-intensity LEDs sourced from Nichia - the world's largest supplier of LEDs based in Japan. The choice of 405 nm LEDs was made after careful consideration of safety. This wavelength is particularly advantageous because, unlike UV light, it is safe for human exposure, and it has been demonstrated to effectively inactivate pathogens such as SARS-CoV-2 and influenza A virus [6].

To ensure the safety and efficacy of the light source, current control via an LED driver is employed, which maintains the intensity within safety thresholds of a maximum of $10 W/m^2$. A lens system is also used based on the distance between the fixture and the disinfection target, as well as the size of the target. This ensures that the light is distributed effectively for disinfection purposes. One of the drawbacks of using 405 nm LEDs for disinfection is the extended duration required for effective decontamination, which can be up to 8 h. However, the ability to use this light source safely in the presence of people is a significant advantage. Additionally, Bluetooth control is being integrated into the system for automation purposes. The light strips, each contain 12 disinfection LEDs and have a dedicated LED driver. A single power supply is used to drive all the strips (Fig. 3).

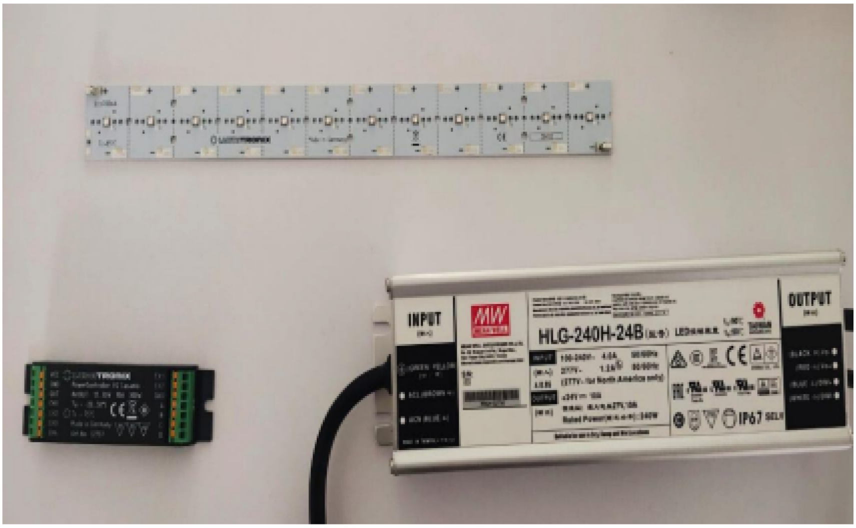

Fig. 3. Strip driver and power supply

4.3 Chamber Design for Efficient Light Distribution

The prototype is meticulously designed to maximize the efficiency of light distribution for disinfection purposes. The doors of the chamber are constructed in a way that allows for full disinfection coverage in a room when the disinfection lights are affixed. When the doors are open, the lights face outward, providing disinfection to the room. When the doors are closed, the lights face inward, disinfecting any items stored within the chamber. This dual-functionality ensures comprehensive decontamination.

The chamber is also designed with flexibility and convenience in mind. It is equipped with wheels, allowing it to be easily moved around a room or facility. This mobility is particularly advantageous for ensuring that all areas of a room can be effectively disinfected. Additionally, the chamber can be fitted with trays, allowing items to be stacked within it during the disinfection process. This is particularly useful for efficiently disinfecting a large number of items at once.

The chamber is equipped with six LED 405 nm strips on each side of the door, ensuring that a large area can be covered by the disinfection light. This is essential for ensuring the efficacy of the disinfection process, particularly given the extended duration required for disinfection with 405 nm light.

Given the safety of 405 nm light for human exposure, and the comprehensive and efficient design of the chamber, it is anticipated that the prototype will be particularly useful in quarantine facilities and other environments where rigorous disinfection is required without compromising human safety.

5 Implementation of Control and Evaluation

In this section, we discuss the implementation of integrating Bluetooth control into the disinfection system of our prototype and evaluate its efficacy in managing scheduling and streamlining the disinfection process. The multipurpose nature of the doors employed is also elaborated on.

5.1 Integration of Bluetooth Control

The prototype features the integration of Bluetooth control aimed at enhancing automation and providing users with the ability to manage the disinfection system remotely via a smart device. To achieve this, a Bluetooth module was incorporated, facilitating communication between the disinfection chamber and a smartphone or tablet.

5.2 Managing Scheduling

The Bluetooth control allows users to manage the scheduling of disinfection processes. This feature is particularly crucial given the extended duration required for disinfection by the 405 nm high-intensity narrow-spectrum light, which can take up to 8 h. The scheduling capability enables users to set the disinfection process during times when the room or facility is not in use, ensuring that the disinfection process does not hinder regular activities.

Furthermore, the system allows for the setting up of recurring schedules, which could prove especially beneficial in institutional settings like hospitals, where it could be programmed to commence disinfection automatically at the end of visiting hours daily.

5.3 Multipurpose Doors

The prototype was meticulously designed to maximize disinfection efficiency. The doors are constructed such that when disinfection lights are affixed, they provide full disinfection coverage within a room when open, and when closed (Fig. 4), they deliver maximum disinfection to any items stored within. Moreover, they have been installed with wheels to facilitate mobility within the room. The doors are thus not only a structural element but also serve a critical function in the disinfection process.

5.4 User Interface and Ease of Use

The Bluetooth control system includes a user-friendly interface on the smartphone or tablet, designed to be intuitive for ease of use. It offers features such as turning the disinfection lights on and off, setting schedules, and monitoring the status of the disinfection process.

5.5 Evaluating Efficacy

In the testing phase, the reliability and responsiveness of the Bluetooth control was evaluated. It was observed that the system promptly responded to commands from the smart device, and the scheduling feature accurately followed the user-set schedules.

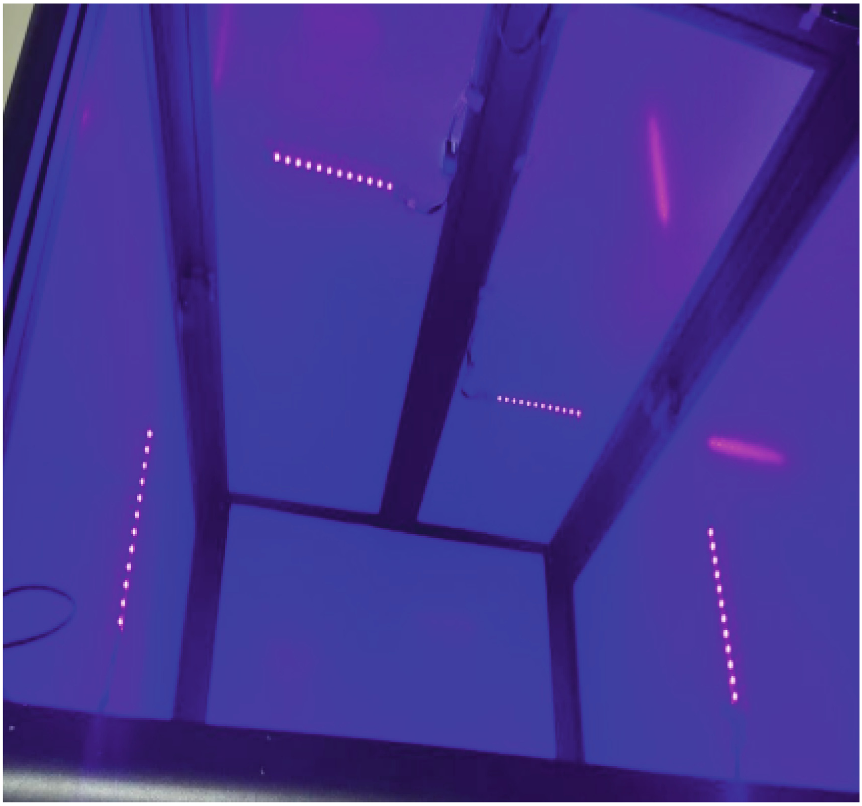

Fig. 4. Enclosed mode

5.6 Discussion

The integration of Bluetooth control and the multipurpose design of the doors in the prototype represent significant advancements in the field of violet light disinfection. The ability to remotely control and schedule the disinfection process enhances convenience and ensures systematic and consistent disinfection, crucial in settings such as hospitals.

While the current design shows promising results, there are areas for potential improvement. Future iterations could include more sensors for real-time feedback on the disinfection process, or integration with facility management systems for further streamlined operations.

In conclusion, the integration of Bluetooth control and the multipurpose nature of the doors in our prototype have proven to be valuable additions to the disinfection system. Their ease of use and reliability in scheduling and managing the disinfection process, as well as their role in efficient light distribution, make them powerful tools in the efforts to maintain clean and sterile environments, particularly in healthcare settings.

6 Practical Applications and Implementation Considerations

In this section, the practical applications of the prototype for disinfection, and the considerations that need to be taken into account for its implementation in various scenarios are discussed. This includes the decontamination of objects, room sterilization, and applications in environmental and healthcare settings.

6.1 Object Decontamination Scenarios

The prototype's design, which employs high-intensity narrow-spectrum light at 405 nm, makes it well-suited for decontaminating objects. In scenarios where it is essential to ensure the sterility of tools, equipment, or other objects, the prototype can be effectively used. For instance:

Laboratories: The prototype can be used to decontaminate laboratory equipment and tools, preventing cross-contamination during sensitive experiments.

Food Industry: In food processing and handling facilities, ensuring the cleanliness of utensils and surfaces is crucial. The prototype can serve as a tool for disinfecting items and surfaces.

Educational Institutions: For educational institutions, especially those with science labs, the prototype can be used to sterilize lab equipment.

6.2 Room Sterilization Possibilities

The mobility and design of the prototype make it versatile enough to be employed in room sterilization. By placing it in a room and engaging its disinfection lights, it can disinfect surfaces and air:

Hospital Rooms: One of the most critical applications could be in hospitals, where preventing the spread of infections is paramount. The prototype could be used to regularly sterilize patient rooms, operation theaters, and isolation wards.

Offices and Workspaces: To maintain a healthy work environment, the prototype could be used to disinfect offices, especially areas with high human traffic such as meeting rooms.

Public Transport: Vehicles such as buses, trains, and airplanes could be sterilized using the prototype to ensure passenger safety.

7 Conclusion

In the final section, the elements of the AMETHYST System are drawn together, summarizing its features and the findings from its deployment. The potential for further advancements and practical implementations in various settings, particularly in underserved areas, is also discussed.

7.1 Summary of AMETHYST System and Findings

The AMETHYST System is a prototype developed to offer a multipurpose, efficient, and safe method for decontamination and sterilization. The key features of this system include:

Multipurpose Doors: The design of the system incorporates doors that serve dual purposes. When open, the doors ensure full disinfection coverage in a room, and when closed, they provide maximum disinfection to any items stored within. This innovative use of space makes the system versatile and highly functional.

High-intensity 405 nm Light: The system employs 405 nm light, which is just beyond the UV range. This high-intensity narrow-spectrum light is known for its germicidal properties while being safer than UV-C light. The choice of this wavelength was made after careful consideration of safety aspects.

Wireless Control: Through the integration of Bluetooth technology, the AMETHYST System can be controlled wirelessly. This allows for automation and ease of use, particularly in settings where manual control is not feasible.

Mobility: The system is designed with mobility in mind, with wheels installed for easy movement around a room or facility. This feature increases its applicability across different scenarios.

Safety and Efficiency: Although the 405 nm light takes longer for disinfection compared to UV-C, it can be used safely in the presence of people, making it suitable for various environments including healthcare settings.

The findings indicate that the AMETHYST System is effective in inactivating pathogens and can be used in various settings, including those with sensitive populations. It offers a balance between safety, efficiency, and versatility.

7.2 Potential for Advancements and Practical Implementation

Applications in Underserved Areas: The mobility and safety features of the AMETHYST System make it particularly suitable for underserved areas where healthcare infrastructure is limited. Its ability to be used safely in the presence of people makes it ideal for community clinics, schools, and other public spaces in resource-limited settings.

Integration with Sensors: Future versions of the AMETHYST System could integrate sensors to detect the level of contamination or the presence of specific pathogens. This would enable more targeted and efficient disinfection processes.

Remote Monitoring and Control: Incorporating IoT technologies could allow for remote monitoring and control of the system, which could be particularly useful in large facilities or in scenarios where the system is deployed in remote areas.

Alternative Power Sources: To increase the applicability in areas with limited or unreliable electricity, the system could be adapted to run on alternative power sources such as solar energy.

Customizable Configurations: Allowing for customizable configurations in terms of light intensity, number of LEDs, and control options could make the system adaptable to specific needs in various settings.

In conclusion, the AMETHYST System represents a significant advancement in decontamination and sterilization technologies. With its multipurpose design, safety features, and wireless control, it holds promise for wide-ranging applications, especially in underserved areas. Further innovations and adaptations can enhance its capabilities and broaden its impact in contributing to public health and safety.

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