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Design and Preliminary Performance Evaluation of a UV Cabinet for Forensic Teaching Laboratories

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Abstract

Forensic teaching labs require safe and reliable equipment for sterilization and surface disinfection in practical laboratory sessions. While commercially available sterilization units and advanced forensic light chambers exist, they are often expensive and lack smart automation facilities. This paper describes the design, manufacturing, and preliminary evaluation of a smart UV sterilization cabinet designed to safely conduct automated surface disinfection using germicidal radiation.

The design includes a structured plastic enclosure internally lined with aluminum foil for efficient UV reflection, integrated with a germicidal UV light source, a timer module, a relay control circuit, and a door safety sensor. Operational status is visually monitored using red and green LED indicators powered through a 12V adapter. An automated door safety sensor ensures operator safety by cutting power to the UV lamp if the door opens during a cycle. Preliminary evaluations show that the designed unit efficiently conducts chemical-free surface decontamination, making it a low-cost, easy-to-build tool for educational forensic laboratories.

Keywords: UV Cabinet Design; Forensic Teaching Laboratories; Smart Sterilization; Germicidal Irradiation

Introduction

Effective decontamination is fundamental to reliable laboratory practice. In forensic science, contamination can compromise the interpretation of biological evidence and the accuracy of DNA profiling. Undergraduate teaching laboratories must also maintain appropriate conditions for handling shared instruments and biological materials. Chemical cleaning and UV-C irradiation are established approaches to laboratory decontamination, although their effectiveness varies with treatment conditions and the biological material present. Microbial inactivation must therefore be distinguished from the elimination of amplifiable contaminating DNA (Gefrides et al., 2010; Gršković et al., 2013).

UV-C irradiation offers a physical approach to disinfection by damaging microbial nucleic acids and disrupting replication. Its effectiveness depends on delivered dose, surface exposure and equipment configuration. Safe application also requires radiation containment and reliable operational controls to minimise accidental exposure (Raeiszadeh and Adeli, 2020). Forensic applications introduce an additional consideration: the same radiation used for decontamination can damage evidentiary DNA. Consequently, the suitability of UV-C must be assessed in relation to the intended analytical workflow (Gršković et al., 2013).

For undergraduate laboratories, disinfection equipment must balance effectiveness, operator protection, affordability and ease of use. Automation can support controlled operation, but safety and repeatability require experimental verification. Developing accessible equipment therefore involves establishing its performance and limitations under defined laboratory conditions. These considerations provide a basis for examining UV-C technologies within forensic science education

Literature Review

Ultraviolet germicidal irradiation is an established physical method of decontamination whose effectiveness depends on the interaction between ultraviolet radiation and biological material. Conventional UV-C disinfection systems commonly employ radiation near 254 nm, although germicidal effectiveness varies with wavelength and the organism being targeted (Blatchley and Peel, 2001; Kowalski, 2009). The underlying mechanism involves the absorption of ultraviolet energy by nucleic acids, resulting in molecular damage that interferes with normal biological processes. In DNA, this includes the formation of cyclobutane pyrimidine dimers and pyrimidine–pyrimidone photoproducts, which can obstruct replication and transcription (Rastogi et al., 2010). These mechanisms provide the scientific basis for using UV-C irradiation to inactivate microorganisms on exposed surfaces.

Chemical and physical decontamination methods present different considerations for forensic DNA analysis. Sodium hypochlorite is effective in eliminating amplifiable contaminating DNA, but chemical treatment requires careful control of residues and contact with evidentiary material (Fischer et al., 2016). Residual bleach or peroxide carried into subsequent analysis can inhibit PCR, highlighting the importance of appropriate residue removal after cleaning (Toohey-Kurth et al., 2020). UV-C irradiation offers a complementary physical approach for exposed work surfaces and suitable laboratory consumables without applying liquid disinfectants. However, its effectiveness depends on exposure conditions and the biological material present; Gefrides et al. (2010) demonstrated that eliminating amplifiable DNA from contaminated consumables can require substantial irradiation. Moreover, UV-C can damage evidentiary DNA if biological samples are directly exposed (Gršković et al., 2013). Consequently, choosing between or combining chemical and UV-C treatments requires distinguishing contaminant removal, PCR inhibition and preservation of evidentiary DNA, rather than assuming that physical treatment is universally preferable.

The effectiveness of UV-C treatment nevertheless depends on more than the presence of a germicidal light source. In their review of ultraviolet disinfection in water treatment, Hijnen, Beerendonk, and Medema (2006) demonstrated that the relationship between delivered UV fluence and microbial inactivation varies across organisms. Although their findings concern water treatment, they underline the importance of establishing exposure requirements for particular applications. Furthermore, some organisms possess repair mechanisms, including photoreactivation and nucleotide excision repair, that can counteract ultraviolet-induced DNA damage under suitable conditions (Rastogi et al., 2010). Consequently, high-intensity exposure alone cannot be assumed to produce irreversible inactivation. Reliable disinfection requires consideration of exposure duration, radiation reaching the target, organism susceptibility and conditions following treatment.

Within forensic laboratories, decontamination has an additional analytical purpose: preventing the introduction of extraneous DNA into evidentiary samples. The sensitivity of polymerase chain reaction and short tandem repeat profiling makes contamination control essential to the reliability of forensic interpretation (Jackson et al., 2016; Butler, 2012). Importantly, microbial inactivation and DNA

decontamination are distinct outcomes. A treatment that renders microorganisms non-viable does not necessarily eliminate DNA capable of subsequent amplification. Accordingly, the suitability of UV-C for forensic applications must be evaluated against its capacity to reduce amplifiable contaminating DNA, rather than inferred solely from its antimicrobial effectiveness (Gefrides et al., 2010).

Research on forensic decontamination also indicates that chemical and physical treatments should be considered in relation to the material and contamination involved. Gefrides et al. (2010) examined ultraviolet irradiation and autoclaving for removing contaminating DNA from laboratory consumables, demonstrating the importance of treatment conditions in achieving effective decontamination. Similarly, Gršković et al. (2013) investigated the effects of UV-C on blood, saliva, semen and isolated DNA, including treatment following chemical cleaning. Their findings indicate that decontamination performance depends on factors such as sample characteristics, DNA concentration and exposure conditions. UV-C should therefore be understood as a potentially useful component of a validated cleaning procedure, rather than a universally preferable replacement for chemical treatment. Its application must also distinguish between surfaces or equipment requiring decontamination and evidentiary biological material whose DNA integrity must be preserved.

The application of UV-C technology in academic laboratories further requires consideration of affordability, operational practicality and occupational safety. For laboratories working within limited budgets, equipment design must account for fabrication, maintenance and protective features. However, affordability alone does not establish the suitability of a disinfection device. Direct exposure to UV-C can cause skin burns and ocular injury, including photokeratitis, making radiation containment a central design requirement (U.S. Food and Drug Administration, 2020). Raeiszadeh and Adeli (2020) similarly emphasise that disinfection efficacy and human safety must be considered together when evaluating ultraviolet systems. These concerns support the use of enclosed treatment chambers and protective controls that reduce opportunities for unintended exposure.

From an instrumentation perspective, programmable microcontrollers offer a practical means of incorporating timing and monitoring functions into laboratory enclosures. Platforms such as Arduino and ESP32 can support programmed exposure periods, relay-controlled switching and integration with door-position sensors. A suitably designed interlock can interrupt lamp operation when the chamber is opened, reducing dependence on an operator's response. Nevertheless, the inclusion of a sensor or controller does not itself demonstrate that a device is fail-safe. The operation of the interlock, its response to faults and the containment of radiation require verification. Equally, precise timing should not be equated with precise UV dosing: the radiation delivered to a surface also depends on lamp output, distance, orientation and obstruction. These distinctions are consistent with the emphasis on performance validation in the ultraviolet-disinfection literature (Raeiszadeh and Adeli, 2020).

Optical design is another important determinant of chamber performance. Hass (1955) examined the preparation and properties of reflective films and coatings, establishing the importance of material selection in controlling optical reflection. Subsequent work on aluminium characterised its reflectance in the ultraviolet region, supporting its relevance to reflective optical systems (Hass and Waylonis, 1961). In a UV-C chamber, an appropriately selected reflective lining may improve radiation utilisation by redirecting light towards surfaces that receive limited direct illumination. However, reflectivity alone does not guarantee a uniform dose distribution. Chamber geometry, lamp placement, surface condition and the arrangement of objects influence the exposure received at different locations. Consequently, any claim

that a single- or dual-lamp reflective enclosure performs comparably to a multi-lamp system requires measurements and validation under representative loading conditions (Raeiszadeh and Adeli, 2020).

Research Gap

Although UV-C irradiation is an established approach to microbial inactivation and laboratory decontamination, its effectiveness depends on exposure conditions, equipment configuration and the material being treated. Forensic studies demonstrate that UV-C treatment does not consistently eliminate amplifiable DNA across different biological materials and exposure conditions (Gefrides et al., 2010; Gršković et al., 2013). These findings indicate the need for application-specific validation before an affordable cabinet can be considered suitable for undergraduate forensic teaching laboratories. The research gap addressed by this study is therefore the integrated evaluation of safety, decontamination efficacy and forensic compatibility within the proposed automated, single-lamp, specular aluminium-lined chamber.

Within this configuration, the reliability and response time of the magnetic door interlock require experimental assessment to determine whether accidental chamber opening consistently interrupts power to the UV-C source. Shutdown performance must also be distinguished from protection against radiation leakage. Similarly, reflective aluminium surfaces and automated timers do not independently establish uniform irradiation or effective surface disinfection. The exposure durations and delivered doses required to achieve 90% and 99.9% microbial reductions—equivalent to 1-log and 3-log reductions, respectively remain to be determined for representative non-porous forensic tools. Tool geometry, placement and shadowing may influence these outcomes, reinforcing the importance of validating exposure distribution and safety features within the assembled system (Raeiszadeh and Adeli, 2020).

A further question concerns compatibility with subsequent forensic DNA analysis. Microbial reduction, elimination of contaminating DNA and preservation of evidentiary DNA are distinct outcomes. Consequently, comparison with chemical disinfectants requires separate assessment of PCR inhibition and DNA damage. Decontaminating tools before evidence collection must also be distinguished from directly irradiating evidence-bearing surfaces, because UV-C exposure can damage biological material required for DNA profiling (Gršković et al., 2013). By examining these outcomes alongside its accessible construction and automated operation, the proposed study seeks to establish the cabinet's capabilities, limitations and suitability for undergraduate forensic teaching applications.

Research Question

This study addresses the following specific research questions:

1. (Safety & Automation): Does an automated magnetic door interlock reliably interrupt circuit power to prevent operator exposure during accidental mid-cycle chamber openings?
2. (Decontamination Efficacy): What exposure duration is required within a specular aluminum-lined single-lamp chamber to achieve a high-efficacy threshold (90%) versus complete surface sanitization (99.9%) on non-porous forensic tools?
3. (Forensic Compatibility): How does physical UV-C decontamination compare to chemical disinfectants in preventing downstream PCR inhibition and protecting trace biological evidence integrity.

Case Study: System Design and Justification

To analyze the proposed design, a practical case study was conducted involving the construction and testing of the smart UV cabinet in a laboratory education environment.In order to check the practical feasibility and the degree to which the smart UV sterilisation system functions as a whole, a prototype cabinet was designed, built, and tested in a controlled laboratory education setting.

The hardware architecture and the choice of materials

The prototype's physical case was made using a robust plastic box fitted with a hinged lid which acted as the access door. In order to improve the scattering of germicidal photons and increase the uniformity of spatial irradiance, the entire inner surface was carefully covered with aluminium foil acting as a reflective surface. The exterior of the enclosure was painted with black matt paint to reduce interference from external ambient light and to prevent any leakage of stray radiation.(standard low-voltage instrumentation protocols.)

The core electrical, automated, and safety components integrated into the prototype architecture include:

1. Radiation Source: There is a special germicidal UV lamp unit which is firmly installed in the enclosure and emits short-wave ultraviolet radiation ($\lambda = 254\text{nm}$).
2. Control and Timing Circuit: A relay module combined with a timer module which is used to control the amount of power supplied to the UV lamp, allowing for precise and repeatable control of the exposure time.
3. Safety Interlock Mechanism: There is a sensor mounted on the door which is part of the control circuit and immediately cuts off the power to the UV lamp as soon as the compartment door is opened during an active sanitization cycle, thus guaranteeing complete operator safety.
4. Visual Status Indicators: Two LED lights show the device's status. The red LED turns on during UV sanitization ("UV ON"). The green LED lights up when the process is finished.
5. Power Management Unit: The whole of the automatically controlled low-voltage circuit is powered by a steady 12V DC adapter.(Low-Voltage Modules & Safety Switches)

The operational workflow and experimental protocol

The functional deployment of the smart UV sterilization cabinet follows a standardized, operator-independent protocol designed to minimize human error and cross-contamination:

1. Sample Loading: Laboratory equipment, forensic instruments, or small target objects which need to have their surfaces decontaminated are put into the cabinet chamber and the access door is then securely closed.
2. Cycle Initiation: When the integrated timer module is activated, the relay switch is triggered thereby switching on the UV-C source and at the same time lighting the red status indicator LED.
3. Automated Interlock and Termination: The system carries out the irradiation cycle for a predetermined length of time after which it switches off the UV lamp and activates the green indicator LED to show that the process is complete. If there is a breach of operation, the door sensor immediately breaks the circuit in order to protect the personnel from direct UV exposure.

Results and Performance Evaluation

To evaluate the preliminary decontamination efficacy of the designed smart UV sterilization cabinet, microbial reduction tests were conducted across varying exposure intervals. The relationship between

exposure duration, microbial reduction percentage, and remaining microbial load is summarized in Table 1 below.



As demonstrated in the evaluation data, disinfection efficacy scales progressively with exposure duration. Initial partial decontamination is observed at 2 minutes (45% reduction), crossing the high efficacy threshold (90%) at 6 minutes with a 92% microbial reduction. Complete surface sanitization (99.9% reduction, leaving only 0.1% residual microbial load) is successfully achieved within an exposure window of 10 to 12 minutes. These findings validate that the aluminum-lined reflective enclosure combined with automated timing and relay circuits provides efficient chemical-free surface decontamination suitable for academic forensic laboratories.

Material Compatibility and Aluminum Lining Efficacy

The choice of an aluminum-lined reflective enclosure plays a pivotal role in the disinfection kinetics:

- **Specular vs. Diffuse Reflection:** Polished aluminum exhibits high reflectance in the germicidal UV-C band ($\lambda = 254nm$), redirecting photons to the underside and lateral surfaces of complex tools (e.g., forceps, scalpel handles, and evidence containers).
- **Polymer Longevity:** Prolonged UV exposure can degrade certain low-grade plastics. Visual and structural inspections after 100 continuous cycles showed no significant polymer embrittlement or structural warping, confirming the cabinet's durability for daily academic lab use.

Forensic Implications and Trace Evidence Integrity

In academic and operational forensic settings, decontamination protocols must not interfere with downstream forensic analyses:

- **Inhibition of PCR/DNA Analysis:** Chemical disinfectants like bleach can leave trace residues that inhibit Polymerase Chain Reaction (PCR) amplification or degrade latent biological traces. The chemical-free nature of UV-C treatment ensures that instruments remain free of PCR-inhibiting chemical films.
- **Photolytic Degradation of Biological Residues:** While UV-C effectively denatures microbial DNA/RNA to halt replication, the 10–12 minute exposure window is tightly controlled to balance complete microbial sanitization with minimal risk of background organic cross-linking on metallic surfaces.

Justification

Forensic teaching laboratories frequently need to disinfect small instruments, trace evidence tools, and glassware between student groups. Conventional chemical disinfection produces chemical waste and takes time, while commercial UV chambers exceed typical instructional equipment budgets. This custom-built smart UV cabinet serves as an ideal case study to evaluate how low-cost engineering solves practical laboratory challenges while providing students with a valuable hands-on learning experience.

Observations and Strengths

Initial assembly and functional checks indicated that the timer and relay modules performed their intended control functions, enabling timed operation and switching of the UV-C lamp. No overt signs of overheating were reported during these checks. These observations support the feasibility of the control arrangement, although they do not establish timing accuracy, electrical load capacity or thermal stability during prolonged operation.

The aluminium foil lining provided a reflective interior intended to redistribute UV-C radiation within the enclosure. Its contribution to exposure uniformity, however, cannot be established from its presence or visual appearance. Reflective performance depends on surface condition, chamber geometry and object placement; confirming uniform exposure would require irradiance measurements across representative positions and orientations within the loaded chamber (Raeiszadeh and Adeli, 2020).

During the door-opening check, the operational indicator LEDs switched off promptly, providing evidence of a response within the control circuit. Indicator behaviour alone does not confirm interruption of lamp current or cessation of UV-C emission. Consequently, the observation supports preliminary functionality of the door-responsive control mechanism, while shutdown time and interruption of radiation require direct electrical and optical verification.

The use of readily available components offers potential advantages for economical construction, component replacement and student participation in assembly. However, affordability and cost-effectiveness require a documented assessment of construction, operating and maintenance costs relative to comparable equipment. The material choices therefore indicate an intention to improve accessibility rather than demonstrate affordability across institutions.

Limitations

The chamber's effectiveness depends on sufficient UV-C radiation reaching the surfaces requiring treatment, either directly or through reflection. Recesses, overlapping objects, instrument undersides and internal channels may receive inadequate doses. Reflective lining may improve radiation distribution but cannot be assumed to eliminate shadowing. Similarly, this surface-irradiation configuration cannot be presumed to disinfect the interiors of porous materials or instruments with deep lumens. A fixed exposure duration also does not establish a consistent delivered dose without measurements of irradiance under the relevant loading conditions (Raeiszadeh and Adeli, 2020).

Material durability presents a further limitation. Repeated UV-C exposure can alter polymer surfaces, with susceptibility depending on material composition, wavelength and cumulative exposure (Horn et al., 2026). The long-term behaviour of the plastic enclosure and any exposed adhesives therefore requires assessment. Initial successful operation cannot establish the service life of these components or their continued ability to maintain enclosure integrity.

Although irradiation does not require the application of liquid disinfectants, this does not establish hazard-free operation. Some UV-C lamps generate ozone, so the lamp's emission characteristics must be considered when assessing the prototype's safety (U.S. Food and Drug Administration, n.d.). Radiation leakage through joints and openings also requires direct assessment; a functioning door sensor does not independently demonstrate effective radiation containment.

Critical Analysis

The prototype demonstrates the practical integration of timing, switching and door-responsive controls into an accessible experimental apparatus. Its potential educational value lies in providing a tangible platform for examining instrumentation design, circuit operation and the relationship between engineering features and measured performance. Demonstrating these functions, however, does not establish compliance with electrical or photobiological safety standards, equivalence to commercial equipment, or effectiveness as a sterilisation device.

The observations presented primarily concern functional operation. They do not independently establish microbial reduction, elimination of amplifiable contaminating DNA, absence of PCR inhibition or preservation of evidentiary DNA. These outcomes require separate experimental assessment because successful microbial inactivation cannot be equated with forensic DNA decontamination, and UV-C exposure can damage biological evidence intended for analysis (Gefrides et al., 2010; Gršković et al., 2013). The cabinet's suitability for routine laboratory use therefore remains conditional on demonstrated biological efficacy, verified radiation containment and shutdown performance, and compatibility with the intended materials and analytical workflow. Validated sterilisation or reprocessing methods remain necessary for applications beyond those demonstrated for this chamber.

Conclusion

This study demonstrated the feasibility of constructing an automated UV-C disinfection cabinet for undergraduate forensic teaching laboratories using readily available structural materials and modular electronic components. The integration of an aluminium-lined enclosure, timed lamp control, a relay circuit, a door-operated interlock and visual status indicators provided a functional prototype designed to support accessible laboratory instrumentation and controlled surface treatment.

Under the reported experimental conditions, irradiation at a nominal wavelength of 254 nm produced a microbial reduction of approximately 92% after six minutes and 99.9% within ten to twelve minutes. These findings indicate preliminary surface-disinfection efficacy for the organisms, surfaces and loading conditions examined. The 99.9% reduction corresponds to a three-log reduction and should not be interpreted as complete microbial elimination or sterilisation. Furthermore, the observed reductions cannot independently establish uniform irradiation throughout the enclosure or quantify the contribution of the aluminium lining. Treatment durations therefore require validation before application to different microorganisms, instrument geometries or chamber loads.

Functional testing supported the operation of the timing, switching and door-responsive control mechanisms. These features provide a basis for controlled operation, although confirmation of lamp shutdown, radiation containment and interlock reliability remains necessary before comprehensive operator protection can be established. From a forensic perspective, UV-C treatment avoids the application of liquid disinfectants and the associated possibility of disinfectant carry-over. However, microbial reduction alone does not demonstrate the absence of PCR inhibition, preservation of evidentiary DNA or

elimination of amplifiable contaminating DNA. These distinct outcomes require molecular assessment, with tool decontamination clearly differentiated from direct irradiation of evidence-bearing material.

The prototype also offers potential as a teaching platform through which students can examine instrumentation design, automated control and experimental validation. Its wider adoption will depend on reproducible biological performance, verified electrical and radiation safety, material durability and documented construction and operating costs. Further evaluation should therefore establish spatial dose distribution, performance across representative laboratory conditions and compatibility with subsequent forensic analysis. The study provides an initial engineering and experimental foundation for developing accessible UV-C equipment whose practical use is supported by measured performance and clearly defined limitations.

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