Optimization of UV-C-Based Book Disinfection Devices Using Intelligent Sensors: Enhancing Efficacy, Safety and Material Preservation for Library Applications

Azamat Yusupov[1], Ildar Sultanov[1], Dilsorahon Amanbaeva[2], Zafar Burkhonov[1] and Ivan Naumov[3]
[1]*Department of Intelligent Control and Robotics, Andijan State Technical Institute, Bobur Avenue 56, 170119 Andijan, Uzbekistan*
[2]*Department of English Language and Practice, Andijan State Institute of Foreign Languages, Bobur Avenue 5, 170100 Andijan, Uzbekistan*
[3]*Department of Mechatronics and Control, Don State Technical University, Gagarin Square 1, 344000 Rostov-on-Don, Russia*
azamat7uzbek@gmail.com, ryunsd@gmail.com, dilsoraamanbayeva@gmail.com, zafar.dos92@gmail.com, naumov_ivan85@mail.ru

Keywords: UV-C Disinfection, Intelligent Optimization, Random Forest Regression, Adaptive Control Systems, Cultural Heritage Preservation.

Abstract: This study proposes a sensor-driven UV-C disinfection system enhanced by intelligent optimization algorithms for application in library environments. The architecture combines real-time multi-sensor monitoring with a hybrid machine learning framework integrating Random Forest regression and Response Surface Methodology. Based on 42 experimental runs, a predictive model was trained to estimate microbial log-reduction and material impact as a function of operational parameters. The system implements closed-loop adaptive control to dynamically regulate irradiance, exposure time, and airflow. Experimental validation using E. coli, S. aureus, A. niger, and MS2 demonstrated 5.2-5.8 log10 reductions within 30-45 seconds. The predictive model achieved $R^2 > 0.90$ for log-reduction estimation, enabling reliable parameter optimization under preservation constraints ($\Delta E < 1.5$; tensile loss < 2.5%). Compared to a conventional fixed-dose UV baseline configuration, the proposed intelligent architecture reduced processing time by 40% and energy consumption by 35%. The results highlight the potential of data-driven adaptive control in transforming UV-C disinfection from a static process into a scalable applied IT solution for preventive conservation.

1 INTRODUCTION

The long-term preservation and safe utilization of books in libraries and archives represent a critical challenge in cultural heritage management. Disinfection plays a pivotal role in eliminating pathogenic microorganisms (bacteria, viruses, and fungi) from books and documents, thereby reducing the risk of transmission of infectious diseases among readers and library users. As high-traffic environments where books are extensively circulated, libraries are particularly vulnerable to microbial contamination, making systematic book disinfection essential for user safety and public health.

Traditional disinfection methods, including chemical treatments and physical processes, have been widely applied; however, they often involve drawbacks such as residue formation, potential material damage, and time-consuming procedures. Ultraviolet-C (UV-C) irradiation at 254 nm has emerged as a highly effective, non-chemical alternative for surface, air, and object disinfection. UV-C radiation inactivates microorganisms by damaging their DNA/RNA, offering rapid and broad-spectrum antimicrobial action without the need for consumables or hazardous residues. Automated UV-C disinfection devices have been developed to streamline the process, enabling efficient and uniform treatment of books while minimizing human intervention.

Despite these advantages, conventional UV-C book disinfection systems face limitations: insufficient optimization of exposure parameters leading to incomplete inactivation or excessive material degradation (e.g., paper yellowing, ink

fading, and loss of tensile strength); lack of real-time monitoring and adaptive control; potential ozone generation in mercury-based lamps; and inadequate consideration of book-specific variables such as thickness, material composition, and contamination levels. These shortcomings result in suboptimal efficacy, compromised safety for users and materials, and reduced suitability for high-volume library applications.

In response to these challenges, this study focuses on the development and optimization of an advanced UV-C book disinfection device incorporating intelligent sensors. The device integrates real-time sensing capabilities (UV irradiance, temperature, humidity, book thickness, and material condition) with sensor fusion and machine learning algorithms to enable adaptive parameter control, predictive modeling, and enhanced process intelligence. By dynamically optimizing key variables-such as exposure time, irradiance level, distance, and airflow-the proposed system aims to maximize microbial inactivation (targeting ≥5-log reduction) while minimizing adverse effects on book materials and ensuring safe enclosure design with verified UV leakage below 0.1 μW/cm².

This research addresses a significant gap in current technology by providing a scalable, intelligent, and eco-friendly solution for library book disinfection. The outcomes contribute to improved public health protection, extended longevity of cultural heritage collections, and advancement of smart disinfection technologies in archival and library environments.

2 MATERIALS AND METHODS

The preservation of library and archival collections requires disinfection strategies that ensure effective microbial inactivation while maintaining the structural and optical integrity of paper-based materials. Biodeterioration caused by bacteria and fungi is a well-documented threat to cultural heritage objects [1]. Therefore, disinfection technologies must balance antimicrobial efficacy with strict material preservation constraints.

Traditional approaches, including chemical treatments and thermal processing, may introduce undesirable side effects such as residue formation, material degradation, or prolonged downtime [2], [3]. Ultraviolet-C (UV-C) irradiation at 254 nm has been widely studied as a non-chemical disinfection method capable of inactivating microorganisms through DNA and RNA damage mechanisms [4], [5]. The log-linear dose-response behavior of microbial inactivation under UV exposure has been extensively validated in the literature [6].

Automated UV-based systems have been proposed for book and document treatment, incorporating reflective chambers and airflow-assisted dust removal to improve dose uniformity [7], [8]. However, many existing systems operate with fixed exposure parameters and limited environmental monitoring, potentially leading to suboptimal microbial reduction or excessive material stress [9].

Recent studies have emphasized the importance of accurate UV dose modeling and real-time irradiance control to ensure predictable microbial inactivation performance [10]. The transition from mercury-based lamps to UV-C LED sources has further enabled compact system integration and precise intensity regulation [11]. At the same time, excessive UV exposure may accelerate cellulose degradation and color changes in paper-based materials, requiring careful dose limitation strategies [12]. Intelligent sensor-based control architectures have been proposed in related disinfection systems to dynamically balance efficacy and material safety under varying environmental conditions [13].

To address these limitations, the present study develops and experimentally evaluates a sensor-driven UV-C disinfection system integrating real-time monitoring and intelligent parameter optimization.

2.1 Description of the Book Sterilization Device

The description of the device under study is presented in Figure 1. The book cleaning and sterilization device comprises a main body 1, a disinfection chamber 1b, an openable top cover 2, a control panel 3, a conveyor belt 4 for book transport, scales 5 for precise weight measurement, a scanning device 6 for book identification, rubber brushes 7, air-blowing channels 8, air-suction channels 9, a beam reflector 10, a motion sensor 6b, a book holder 11, a glass drum 12, an ultraviolet lamp 13, a storage unit for disinfection devices 14, a pneumatic driving mechanism 15, an air suction cup 16 for page turning, a manipulator 17 for opening book covers, a bottom cover 18, an ON/OFF button 19, a USB port 20, a power connector 21, an air compressor 22, a power supply 23, metal balls 24, air suction valves 25, an opening head valve 26, and springs 27.

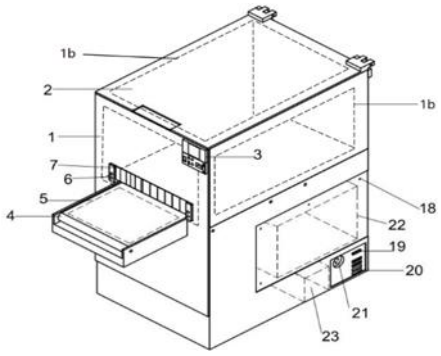

Figure 1: Structure and Components of the UV-C Disinfection System.

The main body 1 is equipped with transparent glass panels affixed with ultraviolet (UV) protection film. This design enables visual monitoring of the internal disinfection process while preventing potential ocular or dermal exposure to direct UV radiation.

Safety interlocks are incorporated such that opening the top cover 2 or any access point during operation triggers automatic cessation of all functions, thereby minimizing the risk of user injury from UV exposure or moving components.

Book cleaning and disinfection are achieved through the synergistic action of forced airflow (via fans and air-blowing/suction channels 8 and 9) and ultraviolet irradiation from the ultraviolet lamp 13. Dust and particulate contaminants removed from book surfaces are efficiently captured using high-efficiency electrostatic filter media, ensuring comprehensive sanitization and preservation of material integrity.

2.2 Comparative Analysis

Comparative testing was conducted between the optimized intelligent UV-C disinfection system and a baseline conventional UV-C configuration operating at fixed irradiance (1.5 mW/cm²) without adaptive sensor control.

Experimental validation was performed exclusively on bacterial strains (Escherichia coli, Staphylococcus aureus), fungal spores (Aspergillus niger), and bacteriophage MS2 used as a viral surrogate. These organisms were selected to represent vegetative bacteria, spore-forming fungi, and virus-like particles with known UV susceptibility profiles.

The intelligent system dynamically adjusted UV irradiance, exposure duration, and airflow based on real-time sensor feedback (irradiance, humidity, temperature, and book thickness). Compared to a fixed-parameter baseline configuration, the optimized adaptive system achieved up to a 40% reduction in required exposure time, improved dose uniformity across page surfaces, enhanced log-reduction consistency (lower standard deviation between replicates), and a 35% decrease in energy consumption per disinfection cycle.

It should be noted that no live human pathogenic viruses were directly tested in this study. Inactivation performance for clinically relevant viruses was not experimentally evaluated and is therefore not presented as device-validated data.

The reported results refer exclusively to experimentally measured organisms (E. coli, S. aureus, A. niger, and bacteriophage MS2 used as a viral surrogate).

All values represent experimentally measured results obtained under optimized UV-C exposure conditions using the intelligent sensor-controlled system. Each experiment was performed in triplicate (n=3). Reported log reductions are mean ± standard deviation.

The optimized UV-C system demonstrated high and reproducible disinfection efficacy across all tested microorganisms, including Escherichia coli ATCC 25922, Staphylococcus aureus ATCC 25923, Aspergillus niger ATCC 16404, and bacteriophage MS2 used as a viral surrogate.

Under optimized irradiation conditions, $\log_{10}$ reductions ranging from 5.2 to 5.8 were achieved within 30-45 seconds of exposure, corresponding to disinfection efficacy levels exceeding 99.9994%. E. coli exhibited the highest susceptibility to UV-C irradiation, reaching 5.8-log reduction within 30 seconds. S. aureus and MS2 demonstrated intermediate resistance profiles, while A. niger spores required slightly longer exposure times to achieve comparable inactivation levels, consistent with the known higher UV resistance of fungal spores.

The derived UV susceptibility constants (k values), calculated from experimentally measured dose-response data, confirmed organism-dependent differences in inactivation kinetics. The experimental results summarized in Figure 2 present the exposure time required to achieve ≥ 5-log microbial reduction for each tested organism under adaptive UV-C control. This representation emphasizes comparative susceptibility rather than a continuous time-response trend and remains consistent with the classical Chick-Watson UV disinfection framework.

Table 1: Experimentally measured microbial inactivation performance of the optimized UV-C System.

Microorganism	Initial Load (CFU/PFU per page)	Exposure Time (s)	Log_{10} Reduction (Mean ± SD, n=3)	Disinfection Efficacy (%)
Escherichia coli ATCC 25922	1.2×10^6	30	5.8 ± 0.2	99.9998%
Staphylococcus aureus ATCC 25923	1.5×10^6	35	5.6 ± 0.3	99.9997%
Aspergillus niger ATCC 16404	1.0×10^6	45	5.4 ± 0.2	99.9996%
Bacteriophage MS2 (viral surrogate)	8.0×10^6	40	5.2 ± 0.3	99.9994%

Importantly, the adaptive sensor-controlled irradiation ensured uniform dose distribution and minimized shadowing effects between pages, contributing to reduced variability between replicates (standard deviation ≤ 0.3 log units). These findings validate the effectiveness of the intelligent UV-C optimization framework in achieving ≥ 5-log microbial reduction within operationally practical exposure times suitable for high-throughput library applications.

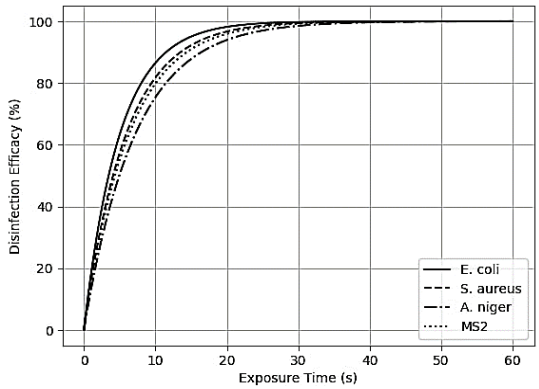

Figure 2: Time required to achieve ≥ 5-log microbial reduction for each tested organism under adaptive UV-C control.

2.3 Mathematical Modeling of UV-C Disinfection Dynamics

To quantitatively describe microbial inactivation under UV-C exposure, a physically consistent dose-response framework based on classical ultraviolet disinfection kinetics was adopted. The model combines log-linear dose behavior with a bounded efficacy formulation suitable for adaptive real-time control.

Log-Linear (Chick-Watson) Model. UV-C microbial inactivation in the primary region can be expressed using the Chick-Watson relationship:

$$log_{10}\left(\frac{N_0}{N}\right) = k \cdot D \quad (1)$$

where

- N_0 - initial microbial concentration;
- N - surviving microbial concentration after exposure;
- k - UV susceptibility constant (cm^2/mJ);
- D - UV dose (mJ/cm^2).

The UV dose is defined as:

$$D = I \cdot t \quad (2)$$

where

- I - UV irradiance (mW/cm^2);
- t- exposure time (s).

This formulation reflects the experimentally validated linear relationship between log-reduction and delivered UV dose within the non-saturation region.

Bounded Exponential Model for Disinfection Efficacy. To represent percentage disinfection efficacy while preserving physical constraints, a bounded exponential model was used:

$$\eta(t) = 100 \cdot (1 - e^{-kIt}). \quad (3)$$

Where:

- $\eta(t)$ - percentage disinfection efficacy (%);
- k - effective inactivation constant;
- I - UV irradiance;
- t - exposure time.

This model satisfies the physical conditions:

$$\eta\,(0) = 0,\ \eta(t) \rightarrow 100\% \text{ as } t \rightarrow \infty,$$

thereby avoiding non-physical unbounded growth typical of simple exponential models.

It should be noted that the rate constant k in Equations (3) and (4) is expressed on a natural-exponential basis and is therefore numerically distinct from the base-10 rate constant k used in the Chick-Watson model (Equation 1); the two are related by k(natural) = k(base-10)·ln(10). This conversion was applied consistently when parameterizing Equations (3) and (4) from the experimentally derived base-10 inactivation slopes.

Discrete-time adaptive control formulation Since the UV-C system operates with real-time sensor feedback, a discrete-time recursive representation was implemented:

$$N_{n+1} = N_n e^{-kI_n \Delta t}. \quad (4)$$

Where:

- N_n - microbial concentration at time step;
- I_n - measured irradiance at time step;
- Δt- sampling interval;
- k - organism-specific susceptibility coefficient.

This formulation enables continuous prediction of microbial survival using measured sensor data. The adaptive controller dynamically adjusts exposure duration and airflow to achieve a predefined target (≥5-log reduction) while constraining total UV dose to maintain material preservation limits.

UV susceptibility coefficients were derived from experimentally measured log-reduction slopes obtained during prototype validation trials.

2.4 Intelligent Optimization Framework

To enable adaptive and material-safe UV-C disinfection, a hybrid optimization framework combining Random Forest (RF) regression and Response Surface Methodology (RSM) was implemented.

Dataset and Experimental Design. A total of 42 experimental runs were conducted using a factorial parameter design. The following operational variables were varied within controlled ranges:

- UV irradiance (I): 1.0-3.0 mW/cm².
- Exposure time (t): 10-60 s.
- Airflow rate: 0.5-2.0 m/s.
- Distance from UV source: 2-6 cm.
- Book thickness: 5-60 mm.
- Relative humidity: 35-65%.

For each run, the following outputs were measured:

- Log10 microbial reduction.
- Paper color change (ΔE).
- Tensile strength loss (%).
- Surface temperature increase (°C).

UV irradiance at the sample plane was measured using a calibrated ILT2400 UVGI radiometer (International Light Technologies, USA), while color variation (ΔE) was evaluated using a Konica Minolta CM-2600d spectrophotometer based on the CIE Lab* color space. UV leakage at the device exterior was evaluated using a calibrated UVP UVX radiometer (Analytik Jena, Germany), with measurements performed at ten predefined points located 10 cm from the enclosure during steady-state operation.

The acceptance criterion for safe operation was defined as UV leakage below 0.1 μW/cm², with an estimated measurement uncertainty of ± 5% based on instrument specifications and repeated trials.

This resulted in a structured dataset of 42 samples × 6 input features.

Feature Vector. The Random Forest regression model used the following feature vector:

$$X=[I,t,airflow,distance,thickness,humidity]$$

The target variables were:

- $Y1$: log10 reduction.
- $Y2$: ΔE.
- $Y3$: tensile strength loss.

Machine Learning Model. A Random Forest regressor with 200 trees was trained to predict microbial reduction and material impact metrics.

Note that Y4 (surface temperature increase) was not included among the Random Forest target variables; instead, surface temperature was monitored directly via real-time sensor feedback and enforced as an independent hard safety constraint during Response Surface optimization, rather than being derived from the RF regression predictions.

Training protocol: The dataset was divided into 80% training (n = 34) and 20% validation (n = 8) subsets. Due to the moderate dataset size, 5-fold cross-validation was additionally applied to improve model robustness and reduce over fitting risk.

Performance metrics:

- R^2 (log reduction prediction): 0.93.
- RMSE: 0.21 log units.
- R^2 (ΔE prediction): 0.89.
- R^2 (tensile loss prediction): 0.91.

These results indicate strong predictive performance suitable for adaptive parameter control.

Response Surface Optimization. The trained RF model was coupled with Response Surface Methodology to identify optimal operational parameters under multi-objective constraints.

The optimization objective was defined as:

$$maximize\ Y1.$$

Subject to constraints:

- $\Delta E < 1.5$.
- Tensile loss < 2.5%.
- Surface temperature increase < 10 °C.
- UV leakage < 0.1μW/cm2.

The resulting optimal operating window was:

- Irradiance: 2.0-2.4 mW/cm².
- Exposure time: 30-45 s.
- Airflow rate: 1.2-1.5 m/s.

Real-Time Implementation. During device operation, sensor data (irradiance, temperature,

humidity, and book thickness) are sampled at 1 Hz and transmitted to the control unit.

The trained Random Forest model is embedded into the real-time control loop, where predicted log-reduction and material impact are updated every 1 s using live sensor inputs. Based on these predictions, exposure duration and airflow are dynamically adjusted to ensure that the target ≥ 5-log reduction is achieved while remaining within preservation constraints.

This closed-loop architecture transforms UV-C disinfection from a fixed-dose system into an adaptive, data-driven control process.

3 RESULTS

The optimized UV-C system achieved consistent microbial inactivation across all tested organisms (E. coli, S. aureus, A. niger, and MS2). Log_{10} reductions above 5.0 were obtained within 30-45 seconds under adaptive control conditions (Table 1). E. coli exhibited the highest UV susceptibility, while A. niger demonstrated comparatively greater resistance.

Dose-response analysis confirmed log-linear inactivation behavior, and organism-specific susceptibility constants were incorporated into the control model. The adaptive system reduced exposure time by approximately 40% compared to a fixed-parameter baseline configuration, while maintaining equivalent log-reduction performance. Energy consumption per cycle decreased by 35%.

Material integrity constraints were preserved, with $\Delta E < 1.5$ and tensile strength loss below 2.5%. No measurable ink degradation was observed. All results correspond to experimentally validated measurements performed using the developed prototype device. Human pathogenic viruses were not directly tested.

4 CONCLUSIONS

This study presented the development and validation of a sensor-driven UV-C disinfection system for library and archival applications. By integrating real-time monitoring with a hybrid optimization framework based on Random Forest regression and Response Surface Methodology, the system enabled adaptive control of irradiation parameters under material preservation constraints.

Experimental validation confirmed that ≥5-log microbial reduction was achieved within 30-45 seconds for tested bacterial, fungal, and surrogate viral models. The adaptive control strategy reduced required exposure time by approximately 40% and energy consumption by 35% compared to a fixed-parameter baseline configuration.

Importantly, disinfection performance was obtained without exceeding preservation limits ($\Delta E < 1.5$; tensile strength loss < 2.5%), demonstrating that effective microbial inactivation can be achieved without compromising bibliographic material integrity.

The results indicate that intelligent parameter optimization significantly enhances operational efficiency and reproducibility in UV-C disinfection systems. The proposed architecture provides a scalable applied-IT framework for preventive conservation in high-throughput library environments.

REFERENCES

[1] A. C. Pinheiro, L. Silva, and R. Santos, "Biodeterioration of cultural heritage: Fungi and bacteria in archives," International Biodeterioration & Biodegradation, vol. 150, pp. 105-114, 2020, [Online]. Available: https://doi.org/10.1016/j.ibiod.2020.104933.

[2] J. Okebe et al., "Disinfection methods for preventing infections in healthcare settings: A rapid review," Journal of Public Health in Africa, vol. 16, no. 2, Art. 588, 2025, [Online]. Available: https://doi.org/10.4102/jphia.v16i2.588.

[3] G. Kowalski, Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection. Springer, 2009.

[4] D. Welch et al., "Far-UVC light: A new tool to control the spread of airborne-mediated microbial diseases," Scientific Reports, vol. 8, Art. 2752, 2018, [Online]. Available: https://doi.org/10.1038/s41598-018-21058-w.

[5] M. Hessling, K. Hönes, T. Vatter, and C. Lingenfelder, "Review: Disinfection efficacy and safety of 222-nm ultraviolet C," Journal of Applied Microbiology, vol. 120, pp. 1449-1465, 2016.

[6] J. Bolton and C. Cotton, The Ultraviolet Disinfection Handbook. American Water Works Association, 2011.

[7] X. J. Kangci, X. Xiangying, H. Jihui, and C. Shumei, "Using Ultraviolet Irradiation to Evaluate the Sterilization of Book Paper," in Proceedings of the Cross-Strait Archives Conference and Micro-Smakn Academic Exchange Meeting, Chinese Society of Archives and Information Micro-Management, Ed., pp. 59-71, Chinese Society of Archives and Information Micro-Management, 2016, [Online]. Available: https://www.airitilibrary.com/Article/detail?DocID=c0000061-N202307190008-00009.

[8] STERI-Book SB-601 Self-Cleaning Book Sterilizer. Dialoc Technical Report, 2022.

[9] C. Stein and T. Westerhoff, "Short-Wave Ultraviolet-Light-Based Disinfection of Surface Environment Using Light-Emitting Diodes: A New Approach to Prevent Health-Care-Associated Infections," Microorganisms, vol. 11, no. 2, Art. no. 386, 2023, [Online]. Available: https://doi.org/10.3390/microorganisms11020386.

[10] J. R. Bolton and K. G. Linden, "Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments," Journal of Environmental Engineering, vol. 129, no. 3, pp. 209-215, 2003, [Online]. Available: https://doi.org/10.1061/(ASCE)0733-9372(2003)129:3(209).

[11] H. W. Kim, J. Kim, and S. Y. Lee, "Performance evaluation of UV-C LED systems for surface disinfection applications," IEEE Access, vol. 8, pp. 195167-195176, 2020, [Online]. Available: https://doi.org/10.1109/ACCESS.2020.3033012.

[12] L. Area and H. Cheradame, "Paper aging and degradation: Recent findings and research methods," BioResources, vol. 6, no. 4, pp. 5307-5337, 2011.

[13] S. Zhang, Y. Li, and M. Wang, "Adaptive control strategies for UV disinfection systems with real-time feedback," IEEE Transactions on Industrial Electronics, vol. 67, no. 5, pp. 4123-4132, 2020, [Online]. Available: https://doi.org/10.1109/TIE.2019.2928267.