

UV-C Dose-Response and Antifungal Efficacy Against *Trichoderma* on Gray Sedge Fibers

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Abstract

Fungal contamination in grey sedge (*Lepironia articulata*) fibers, particularly by *Trichoderma* sp., poses a significant challenge to product quality due to rapid fungal proliferation under humid tropical conditions. Effective fungal control at the early stage of production is therefore essential. This study reports an efficient and environmentally friendly antifungal approach using UV-C irradiation (254 nm) generated by a custom-built device to inactivate *Trichoderma* sp. on the surfaces of contaminated grey sedge fibers, compared with non-irradiated controls. The results demonstrated that antifungal efficacy was dose-dependent, influenced by sample positioning and irradiation time. UV-C doses ranging from 575.3 ± 4.6 mJ/cm² to $2,876.4 \pm 22.8$ mJ/cm² effectively delayed fungal growth, with suppression positively correlated with increasing dose. However, doses $\geq 1,438 \pm 11$ mJ/cm² resulted in a slight reduction in tensile strength. UV-C exposure also induced statistically significant and visually discernible color modifications of sedge surfaces. Notably, doses up to approximately 7,200 mJ/cm² were insufficient to cause significant surface chemical alterations of the grey sedge fibers. These findings highlight the potential of optimized UV-C treatment as a practical non-chemical strategy for controlling fungal contamination in grey sedge fibers while maintaining acceptable material integrity.

Keywords: UV-C irradiation, *Trichoderma* sp., Grey sedge, Natural fiber materials, Antifungal control, Device design

Introduction

Grey sedge (*Lepironia articulata*), locally known as “Krajood” in Thailand, is a perennial aquatic plant that thrives across Southeast Asia, Australia, and parts of Africa [1]. Traditionally harvested from wetlands, this plant has garnered considerable attention for its ecological significance and economic potential [2,3]. Grey sedge fibers are a widely used material in Thai handicrafts, valued for their flexibility, durability, and cultural significance. Notably, it has become a valuable source to produce diverse sustainable products, including furniture, textiles, and home decoration items [4]. However, its high cellulose content and hygroscopic properties make it highly susceptible to fungal

colonization during drying, storage, processing, and during the waiting period for sale or transportation [5]. Among various fungal species, *Trichoderma* is frequently found as a contaminant in grey sedge products such as mats, bags, and various home decorations, due to its rapid sporulation, cellulolytic activity, and ability to thrive under humid conditions. Their presence results in greenish discoloration, surface degradation, and reduced commercial value of grey sedge products.

Currently, *Trichoderma* species have gained substantial scientific attention due to their wide-ranging applications in agriculture, biotechnology, and

environmental management [6-8]. These fungi exhibit strong antagonistic activity against plant pathogens and play key roles in promoting plant growth, enhancing nutrient uptake, and inducing systemic resistance. Their robust enzymatic machinery—particularly cellulases and chitinases—also underpins their industrial relevance and contributions to biodegradation processes. Despite this importance, studies focusing on *Trichoderma* contamination in grey sedge fibers are notably limited, even though such infestations pose practical challenges for local producers. *Trichoderma* spp. produces highly active cellulases and chitinases that accelerate fiber decomposition, leading to reduced mechanical strength and compromised aesthetic quality of natural fiber products [9,10]. Recent studies have shown that *Trichoderma* can rapidly degrade lignocellulosic substrates through synergistic hydrolytic enzyme systems [11]. Furthermore, *Trichoderma* contamination also introduces health concerns, as airborne *Trichoderma* spores can trigger allergic reactions and respiratory irritation, especially in sensitive individuals [12,13]. To avoid these potential problems, it is essential to prevent or inhibit fungal growth on materials used in grey sedge products.

Various methods have been explored and reported to address mold growth in sedge products, including the use of chemicals such as sodium hypochlorite or benzoic acid to reduce mold growth [14,15], biological and microbial control, such as *Trichoderma harzianum* [16], and herbal smoking or fumigation [17]. Furthermore, packaging design that protects against moisture during transportation can significantly reduce mold growth [18]. In addition, coating the surface of grey sedge products with the polymer P(VDF-HFP) is another method that can reduce the risk of fungal growth [19]. However, UV-C irradiation for fungal inhibition has been gaining widespread attention because it is chemical-free, fast-acting, broad-spectrum, minimally thermal, and highly scalable. UV-C radiation, especially at 254 nm, has been shown to disrupt the structural integrity of nucleic acids—DNA and RNA—in various pathogenic organisms, including fungi, viruses, and bacteria [20]. UV-C directly damages DNA and RNA by forming cyclobutane pyrimidine dimers and 6 - 4 photoproducts, which hinder replication and transcription. Consequently, this leads to cell death or a loss of infectivity [21].

Previous research has demonstrated the effectiveness of UV-C in reducing fungal growth in food commodities, agricultural materials, and packaging [22,23]. Specifically, UV-C treatment has been shown to significantly reduce the survival fraction of fungal spores [24], and studies suggest its potential to suppress fungal enzyme production and biodeterioration in various substrates [25]. However, reports on the use of UV radiation to control *Trichoderma* sp. growth on grey sedge fiber surfaces remain limited. Additionally, existing UV systems are generally commercially manufactured, expensive, and not well-suited for small-scale, practical treatments of natural-fiber products. These gaps highlight the need to develop and test UV-based methods specifically designed to inactivate *Trichoderma* sp. found on grey sedge surface fibers.

This study makes 3 key contributions to the field. First, it introduces a custom-built, low-cost UV-C treatment device capable of delivering controlled, reproducible irradiation for inactivating *Trichoderma* sp. on grey sedge fibers. By combining modern UV-C engineering principles with published fungal inactivation kinetics [26-28], the device is designed for practical use in resource-limited settings. Second, the study showcases a novel application of UV-C irradiation to grey sedge fibers, a natural material that has received limited scientific attention despite its importance for sustainable fiber-based products. Third, it systematically examines the trade-off between antifungal efficacy and the preservation of key material properties, clarifying how UV-C processing influences both biological resistance and the structural integrity of grey sedge fibers. Together, these contributions advance current understanding of UV-C-based bioprotection strategies for natural fiber materials.

Materials and methods

Grey sedge material

Dried grey sedge fibers were obtained from a local farmer group in Cha-ua District, Nakhon Si Thammarat Province, Thailand, engaged in the production of grey sedge-based products for commercial purposes. Prior to sample preparation, the grey sedge fibers were dried to remove residual moisture. The dried grey sedge fibers were cut to 4 cm lengths. All prepared samples were stored in a clean, dust-free environment prior to testing under the specified experimental conditions.

UV-C irradiation chamber design

A custom-built UV-C irradiation chamber was developed for controlled surface-treatment experiments (**Figure 1**). The chamber was fully enclosed and fabricated with SUS 304 food-grade stainless steel for both the inner and outer walls, providing mechanical durability, ease of sanitation, and high UV-C reflectivity to improve irradiation uniformity. The interior surfaces were polished stainless steel, and the sample-to-lamp distance was adjustable from 5 to 45 cm to allow precise control of irradiation conditions. The internal dimensions of the chamber were 60×60×60 cm³, ensuring sufficient space for exposure while preventing external light interference and UV leakage. UV-C

radiation was generated using 3 low-pressure mercury lamps (PHILIPS TUV T8), each rated at 16.7 W and emitting predominantly at 254 nm. The lamps were mounted horizontally at the bottom of the chamber, with one lamp centrally positioned and 2 additional lamps symmetrically arranged on either side, each at a 20 cm spacing from the central lamp. Irradiation time was controlled using a programmable timer, while chamber temperature was continuously monitored by an integrated temperature sensor. Lamp operation was controlled via an on-off system, ensuring stable, reproducible UV-C exposure throughout the experiments.

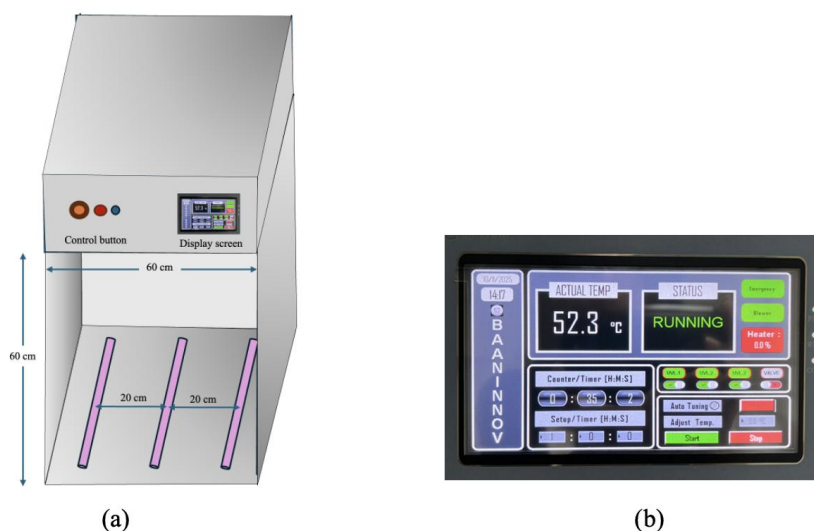


Figure 1 Custom-built UV-C irradiation system. (a) Schematic diagram of the irradiation chamber showing chamber dimensions, the arrangement of 3 UV-C lamps at the base, and integrated control components, (b) detailed view of the display screen.

Pre-irradiation time of UV-C treatment

To determine the stabilization period of UV-C lamp operation, simultaneous measurements of UV-C irradiance and temperature were conducted under controlled conditions. The experiment was performed using a single UV-C lamp, operated independently at the central position of the irradiation chamber. The UV-C irradiance sensor was positioned 10 cm above the lamp center, with the sensor surface perpendicular to the lamp plane to ensure consistent measurement geometry. UV-C irradiance and temperature were quantitatively measured using a calibrated UV radiometer (TENMARS TM-218, Taiwan), following standardized procedures to ensure accurate and reproducible data.

Data acquisition began immediately after the UV-C lamp was switched on and continued continuously for 1,200 s, capturing the lamp warm-up phase and the subsequent transition to steady-state operation. Each experiment was conducted in triplicate under identical operating conditions. The stabilization period was defined as the time required for UV-C irradiance to reach and maintain a constant output with minimal temporal fluctuation, indicating stable lamp performance. This measurement approach provides essential information for defining appropriate pre-irradiation times in UV-C treatment experiments.

Spatial distribution of UV-C irradiance within the irradiation chamber

The spatial distribution of 3-lamp UV-C irradiance levels within the irradiation chamber was systematically analyzed in both vertical and horizontal directions. Vertical UV-C irradiance profiles were obtained by positioning the UV sensor probe directly above the lamp plane along the central axis of the chamber. As shown in **Figure 2**, the red points represent the measurements taken at adjustable vertical distances in 5 cm increments, ranging from 5 to 30 cm above the lamp surface. At each height, the sensor was oriented perpendicular to the irradiation plane to ensure consistent measurement geometry. This approach enabled the evaluation of

irradiance attenuation as a function of distance from the UV-C source.

Horizontal irradiance distribution was evaluated at a fixed vertical distance of 10 cm above the lamp plane, as depicted in **Figure 2** with blue points. At this height, UV-C intensity was measured horizontally across the chamber's width, encompassing positions above the central lamp and symmetrically distributed on the left and right sides. This measurement enabled assessment of lateral irradiance uniformity resulting from the 3-lamp configuration. All measurements were conducted under identical operating conditions after the UV lamps reached stable output. Each measurement position was tested in triplicate, and the mean irradiance values, along with their standard deviations, were calculated.

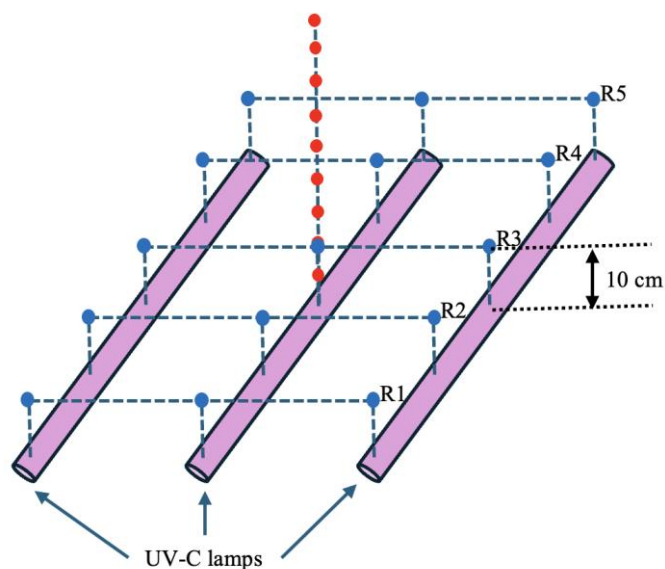


Figure 2 Schematic illustration of UV sensor positioning within the irradiation chamber. Blue points indicate horizontal measurement locations, while red points represent vertical measurement locations used for UV-C irradiance mapping.

Effects of UV-C irradiation on physical and mechanical properties of grey sedge fibers

The effects of UV-C irradiation on the physical and mechanical properties of grey sedge fibers were investigated using a custom-built UV-C irradiation chamber. The UV-C irradiation process was initiated by warming up the irradiation system, during which all 3 UV-C lamps were switched on for at least 3 min to allow the system to reach a stabilization period prior to sample exposure. Grey sedge fiber samples were then positioned at the center of the irradiation chamber, directly above the middle lamp, at a vertical distance of

10 cm from the lamp plane. The samples were irradiated for 10, 20, 30, 40, and 50 min to evaluate time-dependent UV-induced changes. The UV-C dose (D) received by the grey sedge fibers was calculated according to the relationship $D = I \times t$, where I represents the UV-C irradiance measured at the sample position and t denotes the exposure time. Non-irradiated fibers were used as control samples. Following UV-C treatment, all samples were allowed to equilibrate at room temperature for at least 24 h prior to physical and mechanical testing, to minimize the influence of environmental factors. The irradiated and control fibers

were subsequently analyzed for surface wettability, color change, and tensile strength analyses. Each experimental condition was conducted in triplicate. Results were expressed as mean $\pm$ standard deviation.

Surface wettability

Surface wettability of the grey sedge fiber samples was evaluated using a contact angle goniometer (OCA 15EC, DataPhysics Instruments, Germany) equipped with a high-resolution camera and automated image analysis software. Static water contact angle measurements were performed using the sessile drop method. A droplet of deionized water with a fixed volume of 1 μ L was carefully dispensed onto the surface of each sample using a calibrated microsyringe. The left and right contact angles were determined automatically by the OCA analysis software, and the mean value was recorded as the representative water contact angle for each measurement. For each experimental condition, measurements were repeated 5 times at different locations on the sample surface to account for surface heterogeneity. The average water contact angle and standard deviation were calculated for each group.

Color characteristics

Surface color changes induced by UV-C irradiation were measured using a colorimeter operating in the CIELAB color space. The parameters L^* (lightness), a^* (red-green), and b^* (yellow-blue) were recorded at 3 randomly selected positions on each sample, and mean values were reported. The total color difference (ΔE^*) relative to the untreated control was calculated using the following equation:

$$\Delta E^* = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

where L_0^* , a_0^* , and b_0^* represent the color coordinates of the control samples.

Tensile strength

Tensile strength characterization of grey sedge fibers was carried out to assess the mechanical performance of both untreated samples and those treated with UV-C irradiation for 10 - 50 min. Uniaxial tensile measurements were performed using a Tensile Testing Machine (Z010, ZwickRoell, Germany) equipped with

a 1.0 kN load cell, operated at a constant crosshead speed of 10 cm/min under ambient conditions. For each experimental condition, 3 independent specimens were tested to ensure the reliability and reproducibility of the results. The tensile stress (σ) was calculated according to $\sigma = F/A$, where F represents the applied force and A is the original cross-sectional area of the specimen. The tensile strain (ϵ) was determined from $\epsilon = \Delta L/L_0$, where ΔL denotes the change in gauge length and L_0 is the initial gauge length [29]. The resulting stress-strain curves were analyzed to determine the tensile strength and deformation characteristics of the grey sedge fiber samples.

Effects of UV-C irradiation on the inactivation of *Trichoderma* sp.

The custom-built UV-C irradiation chamber was applied to evaluate its effectiveness in inhibiting *Trichoderma* sp. on the surface of grey sedge fibers. The experimental procedure comprised 3 main stages: (i) preparation and inoculation of *Trichoderma* on the sedge fiber surface, (ii) UV-C irradiation treatment under controlled exposure conditions, and (iii) evaluation of the effects of UV-C exposure on fungal viability.

Preparation and inoculation of *Trichoderma* sp. on the grey sedge fiber surface

Grey sedge fiber samples were subjected to a pre-treatment sterilization process to eliminate indigenous fungal contamination on both the fiber surfaces and the internal structure. Sterilization was performed using an autoclave under high-pressure steam conditions at 121 °C and 15 psi for 15 min. Following sterilization, all samples were cooled to room temperature and stored under clean-room conditions prior to fungal inoculation. A *Trichoderma* sp. strain previously isolated from the surface of dried grey sedge was used in this study (Faculty of Science and Technology, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat, Thailand). Fungal spores were produced by culturing the isolate on malt extract agar (MEA; HiMedia, Thailand) at 30 °C for 7 days. Spores were harvested by flooding the culture surface with 5 mL of sterile saline solution (8.5 g L⁻¹ NaCl) supplemented with 0.1% (v/v) Tween 80, followed by gentle scraping to release conidia. The spore suspension was filtered to

remove mycelial fragments and enumerated using a hemocytometer. The suspension was then adjusted to a final concentration of 1×10^6 spores mL^{-1} by dilution with sterile distilled water. The viability of the fungal spores was confirmed by quantitative plate count analysis, yielding an initial population of approximately 1×10^6 CFU mL^{-1} prior to UV-C irradiation. Sterilized grey sedge fiber samples were inoculated by uniformly applying 50 μL of the conidial suspension onto the surface of each sample and resting for 2 h before treatment.

UV-C irradiation treatment

Grey sedge fiber samples, prepared and inoculated with *Trichoderma* sp., were subjected to UV-C irradiation to assess the efficacy of fungal inhibition. These samples were placed horizontally at a fixed distance of 10 cm above the UV-C lamp plane within a custom-built irradiation chamber. The chamber maintained a consistent UV intensity of $2,397 \pm 19 \mu\text{Wcm}^{-2}$ to ensure uniform exposure conditions. To minimize the impact of UV radiation on the physical and mechanical properties of grey sedge fibers, the samples were exposed for 4, 8, 12, 16, and 20 min. These exposure times were chosen based on calculated UV doses determined using the equation $D = I \times t$, resulting in 5 doses of $575.3 \pm 4.6 \text{ mJ/cm}^2$, $1,150.6 \pm 9.1 \text{ mJ/cm}^2$, $1,725.8 \pm 13.7 \text{ mJ/cm}^2$, $2,301.1 \pm 18.2 \text{ mJ/cm}^2$, and $2,876.4 \pm 22.8 \text{ mJ/cm}^2$. The exposure duration was precisely controlled using an integrated timer to ensure accurate and reproducible dose delivery. In addition, temperature and relative humidity were recorded throughout the experiment to monitor environmental conditions during the treatment. Immediately after irradiation, the treated samples were aseptically transferred to sterile Petri dishes and incubated in the dark by covering the dishes with aluminum foil to prevent photoreactivation. Each treatment was conducted in triplicate. Inoculated samples that did not receive UV-C exposure served as the control group. The inhibitory effects of UV-C irradiation were evaluated by comparing fungal growth between irradiated and non-irradiated samples.

Evaluation of the effects of UV-C exposure on fungal viability

The effects of UV-C exposure on fungal viability were evaluated through time-lapse visual monitoring using a digital camera. Grey sedge fiber samples inoculated with *Trichoderma* sp. were assigned to experimental groups: a non-irradiated control group and UV-C-treated groups exposed to 5 UV-C doses. Following UV-C treatment, both irradiated and non-irradiated samples were placed in sterile Petri dishes. The Petri dishes were subsequently covered with aluminum foil to prevent unintended light exposure and were opened only during image acquisition. All samples were stored in the same clean room maintained at 26 - 29 °C and 69% - 74% relative humidity throughout the observation period. Digital images of fungal growth on the grey sedge surface were captured at 8-hour intervals over 3 days (72 h) using the same digital camera, fixed imaging distance, illumination conditions, and camera angle to ensure consistency and comparability across time points and treatments. The captured images were used to qualitatively compare fungal colonization, mycelial expansion, and visible sporulation between the control group and the UV-C-treated groups at different dose levels. Changes in fungal viability were evaluated by comparing the temporal progression of fungal growth, enabling visualization of dose-dependent growth delay or inhibition induced by UV-C irradiation. Along with qualitative observations of fungal growth, a quantitative assessment of fungal proliferation was conducted by measuring the surface area covered by *Trichoderma* sp. on the culture medium. Digital images captured during incubation were analyzed using ImageJ software to determine the percentage of fungal coverage. For each experimental condition, 3 independent samples were examined ($n = 3$), and the average fungal coverage values were used for subsequent statistical analysis.

Results and discussion

Pre-irradiation time of UV-C treatment

The intensities of UV-C radiation and air temperature at a fixed distance of 10 centimeters above the center of the lamp, as depicted in **Figure 3**, are presented. The results indicate that UV-C irradiance (represented by the blue line) increased rapidly during the initial phase after lamp activation. Within

approximately 100 to 200 s, it reached near-maximum levels. This behavior is attributed to the stabilization of mercury vapor pressure and discharge conditions within the lamp. Subsequently, the UV-C irradiance reached a steady state, making it the optimal period for material irradiation. In contrast, the temperature of the UV-C lamp (orange line) gradually increased throughout the entire 1,200 s irradiation period due to continuous heat accumulation during electrical discharge. As the lamp temperature increased, a slight decrease in UV-C irradiance was observed, suggesting a minor inverse relationship between temperature rise and UV-C output during prolonged operation, which can be explained by excessive mercury vapor pressure at elevated

temperatures, leading to reduced emission efficiency at the germicidal wavelength. These results indicate that although UV-C output stabilizes after the warm-up phase, prolonged operation and temperature increases may slightly reduce irradiance, underscoring the need to define an appropriate stabilization period prior to treatment. Additionally, elevated lamp temperatures can reduce UV-C output by altering mercury vapor pressure, highlighting the importance of controlling both irradiation geometry and operating conditions. This finding is consistent with previous studies demonstrating that elevated lamp temperatures reduce UV irradiance by decreasing radiant efficiency [28,30].

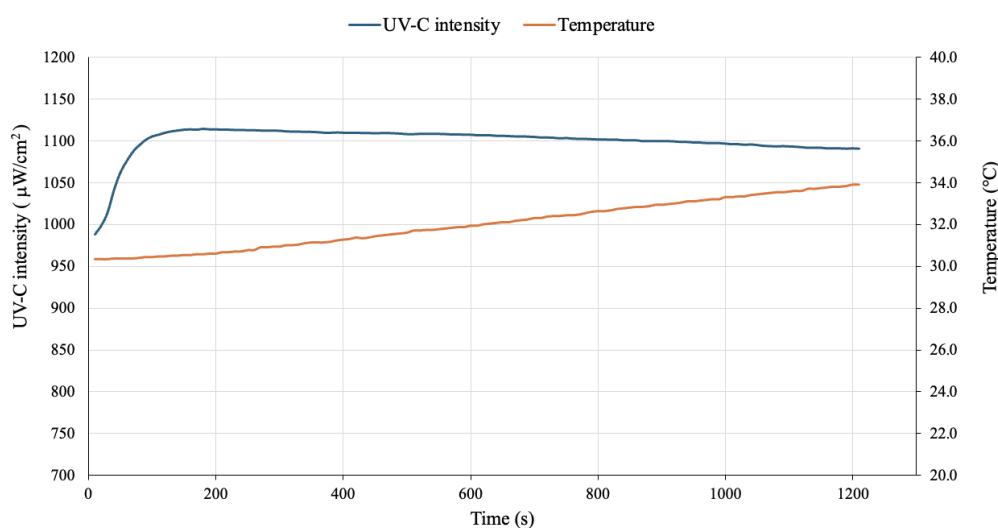


Figure 3 UV-C irradiance (left axis, $\mu\text{W}\cdot\text{cm}^{-2}$) and chamber temperature (right axis, $^{\circ}\text{C}$) as a function of exposure time (s). Irradiance increases rapidly and stabilizes at $\approx 1,100 - 1,120 \mu\text{W}\cdot\text{cm}^{-2}$ within $\sim 100 - 200$ s, then declines slightly to $\approx 1,090 \mu\text{W}\cdot\text{cm}^{-2}$ by 1,200 s. Temperature increases gradually from ≈ 30.0 to ≈ 34.0 $^{\circ}\text{C}$ over the 1,200 s period.

Spatial distribution of UV-C irradiance within the irradiation chamber

The UV-C irradiance distribution within the custom-built irradiation chamber showed distinct patterns that varied with distance and position. As shown in **Figure 4(a)**, the vertical irradiance profile showed a progressive decrease in UV-C intensity with increasing distance from the lamp plane. The highest irradiance was observed at positions closest to the UV-C source, followed by gradual attenuation as the measurement height increased to 30 cm. This behavior is consistent with geometric radiation divergence and minor absorption losses in air, confirming that vertical distance is a critical factor influencing the effective UV-

C dose delivered to the sample surface. This trend is consistent with previous studies showing that UV-C irradiance decreases significantly with increasing distance from the lamp, which is the primary factor governing irradiance distribution [30,31].

The horizontal irradiance distribution measured at the same vertical distance revealed a non-uniform UV-C irradiance distribution across the horizontal plane, as shown in **Figure 4(b)**. The central lamp emitted the highest irradiance, while the irradiance gradually decreased as one moved towards the distal ends of the lamp array. This phenomenon can be attributed to the geometric advantage at the lamp center, where radiation is received from both directions along the lamp's length

[32]. This non-uniformity is further influenced by the axial emission profile of each lamp, where the positive column in the mid-section produces stronger UV-C output than the electrode regions near the ends, resulting in reduced irradiance at the lamp extremities [33]. Additionally, the irradiance above the center of the middle lamp was higher than that above the centers of the left and right lamps due to the symmetrical contribution of UV-C flux from neighboring lamps on both sides. On the other hand, the outer lamps received supplemental radiation from only one adjacent source. Overall, irradiance tended to decrease progressively as one moved from the center towards the ends of each lamp and shifted away from the central axis of the lamp array. These findings are consistent with the radiometric behavior of linear emitters and with the inverse-square law governing the spatial attenuation of radiation.

The non-uniform distribution of UV-C irradiance across the chamber has significant implications for dose delivery and experimental reproducibility. Since UV-C dose is directly proportional to irradiance and exposure time, similar spatial dose heterogeneity has been observed in UV-C disinfection systems [32]. This

highlights the importance of precise sample positioning, irradiance mapping, or rotational exposure to ensure uniform treatment. Spatial non-uniformity in UV intensity can significantly influence the reliability of fungal inactivation. If UV fluence is not evenly distributed across the exposure area, some regions may receive lower doses than intended. Fungal spores located in these under-exposed zones may survive the treatment, leading to incomplete or inconsistent inactivation. This effect is particularly important for filamentous fungi, whose spores can cluster or adhere unevenly to surfaces, further amplifying the impact of dose variability. For practical deployment, particularly in artisanal production or small-scale industries processing grey sedge products, the system could be operated by arranging materials within the central irradiation region or by periodically rotating the samples to ensure uniform exposure. Such operational strategies can effectively compensate for spatial variations in irradiance. Therefore, in this study, all grey sedge samples were consistently placed at the central irradiance maximum to minimize variability and accurately assess the dose-response relationship.

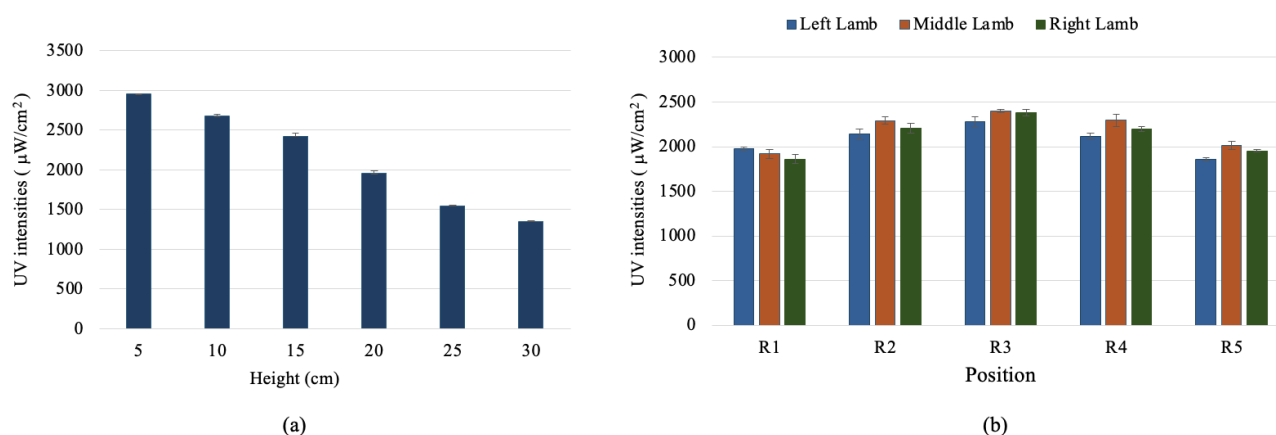


Figure 4 Spatial distribution of UV-C irradiance within the irradiation chamber. (a) Vertical irradiance profiles at distances of 5 - 30 cm above the lamp plane. (b) Horizontal irradiance distribution across the chamber width at a fixed height of 10 cm.

Effects of UV-C irradiation on physical and mechanical properties of grey sedge fibers

The physical and mechanical properties of grey sedge fibers following UV-C irradiation were systematically evaluated to determine the extent of UV-induced alterations. The assessment focused on 3 key

parameters: Surface wettability, color characteristics, and tensile strength. UV-C exposure time was varied to examine dose-dependent effects on the fibers' physical appearance and mechanical integrity, with non-irradiated samples used as controls. All irradiated specimens were positioned at the central point of the

middle lamp (R3 of the middle lamp; **Figure 4(b)**), corresponding to the highest measured irradiance within the chamber. The UV-C intensity at this location was $2,379 \pm 19 \mu\text{W}\cdot\text{cm}^{-2}$, and exposure times of 10, 20, 30, 40, and 50 min were applied, yielding calculated surface doses ranging from $1,438 \pm 11$ to $7,191 \pm 57 \text{ mJ}/\text{cm}^2$. The corresponding results and discussion are presented below.

Surface wettability

The results of water contact angle measurements for grey sedge fibers subjected to UV-C irradiation for 10, 20, 30, 40, and 50 min, corresponding to UV-C doses calculated according to the relationship $D = I \times t$, as well as for non-irradiated control samples, are presented in **Table 1**. The non-irradiated control exhibited a water contact angle (WCA) of $90.2^\circ \pm 0.5^\circ$, indicating a nearly neutral wetting behavior. However, after exposure to UV-C radiation at doses ranging from $1,438 \pm 11 \text{ mJ}/\text{cm}^2$ to $7,191 \pm 57 \text{ mJ}/\text{cm}^2$, the WCA values remained within a narrow range of 89.6° - 89.9° , showing no clear dose-dependent trend. Statistical analysis using one-way

ANOVA (Single Factor) confirmed that the differences among groups were not statistically significant ($F = 0.474$; $p = 0.789$). This suggests that UV-C irradiation within the tested dose range did not significantly affect the surface wettability of grey sedge fibers. The minimal variation ($\leq 0.6^\circ$ difference from control) indicates that the surface energy and hydrophilic-hydrophobic balance of the fibers remained largely unchanged.

These findings suggest that UV-C doses up to approximately $7,200 \text{ mJ}/\text{cm}^2$ were insufficient to induce significant surface chemical modifications, such as the formation of additional oxygen-containing functional groups that could alter wettability [32,34]. While UV-induced photo-oxidation can modify lignocellulosic surfaces under specific conditions, the present results indicate that at the applied irradiation levels, grey sedge fibers retained their inherent surface characteristics. This preservation of wettability is advantageous for practical applications, as antifungal treatment can be achieved without compromising surface interaction properties that are crucial for downstream processing or product performance.

Table 1 Water contact angle of grey sedge (*Lepironia articulata*) fibers after UV-C irradiation at different exposure times and doses, showing minimal changes in surface wettability across all treatments. Values are expressed as mean $\pm$ SD.

Sample	Treatment time (min)	UV-C dose (mJ/cm^2)	Water contact angle (degree)
Control	0	0	90.2 ± 0.5
UV-C_10	10	$1,438 \pm 11$	89.8 ± 1.1
UV-C_20	20	$2,876 \pm 23$	89.9 ± 0.6
UV-C_30	30	$4,314 \pm 34$	89.8 ± 0.6
UV-C_40	40	$5,752 \pm 45$	89.9 ± 0.9
UV-C_50	50	$7,191 \pm 57$	89.6 ± 0.8

Effect of UV-C dose on color changes of grey sedge fibers

The effects of UV irradiation on the colorimetric properties of the grey sedge surface were evaluated using the CIELAB parameters ΔL , Δa , Δb , and the overall color difference ΔE . The samples were exposed for 10 - 50 min, corresponding to UV-C doses of $1,438 \pm 11 \text{ mJ}/\text{cm}^2$ - $7,191 \pm 57 \text{ mJ}/\text{cm}^2$, calculated using the

equation $\text{Dose} = \text{intensity} \times \text{time}$. The mean values and standard deviations (SD) obtained from triplicate measurements ($N = 3$) for each UV-C dose level and the control group are summarized in **Table 2**. The one-way ANOVA results showed statistically significant differences among treatment groups for ΔL , Δb , and ΔE , whereas Δa showed no significant differences.

Table 2 Colour differences (ΔL , Δa , Δb , and ΔE) of grey sedge (*Lepironia articulata*) fibers after UV-C irradiation. Values are expressed as mean $\pm$ SD ($n = 3$). Statistical significance was determined by one-way ANOVA.

Samples	ΔL (Mean $\pm$ SD)	Δa (Mean $\pm$ SD)	Δb (Mean $\pm$ SD)	ΔE (Mean $\pm$ SD)
Control	0.000 $\pm$ 0.000	0.000 $\pm$ 0.000	0.000 $\pm$ 0.000	0.000 $\pm$ 0.000
UV-C_10	-3.7767 $\pm$ 0.727	-0.2067 $\pm$ 0.320	-3.4567 $\pm$ 0.519	5.1347 $\pm$ 0.858
UV-C_20	-3.2167 $\pm$ 0.205	-0.5300 $\pm$ 0.139	-2.5367 $\pm$ 0.335	4.1435 $\pm$ 0.120
UV-C_30	-3.4233 $\pm$ 0.779	-0.2533 $\pm$ 0.540	-3.0333 $\pm$ 0.444	4.6527 $\pm$ 0.318
UV-C_40	-3.0900 $\pm$ 0.235	-0.5167 $\pm$ 0.321	-3.1433 $\pm$ 0.283	4.4478 $\pm$ 0.327
UV-C_50	-2.8567 $\pm$ 0.200	-0.0933 $\pm$ 0.461	-2.7900 $\pm$ 0.979	4.0405 $\pm$ 0.808
Statistical parameter: F	26.59	1.17	17.68	39.13
Statistical parameter: p	4.23×10^{-6}	0.38	3.63×10^{-5}	5.06×10^{-7}

ANOVA revealed a highly significant effect of UV-C irradiation on ΔL ($p < 0.00001$), with all treated samples exhibiting negative ΔL values, indicating consistent surface darkening. This response is attributed to early-stage lignin photodegradation and to the formation of conjugated chromophores that enhance visible-light absorption and reduce reflectance, as reported by Yao *et al.* [35]; Feng *et al.* [45] and Fazeli *et al.* [49]. The low within-group variability further suggests a uniform photochemical response of grey sedge fibers to UV-C exposure. In contrast, Δa showed no significant differences among treatments ($p = 0.379$). Although a slight shift towards green was observed, the magnitude remained within natural variability. This stability implies that the chromophores governing the red-green axis are less sensitive to UV-C radiation, likely due to their limited penetration depth and the selective absorption characteristics of phenolic compounds and extractives [36,38,45]. Δb was significantly affected by UV-C treatment ($p < 0.0001$), with all irradiated groups showing negative values, reflecting a shift towards blue hues. This change corresponds to the degradation of yellow-brown chromophores derived from lignin and extractives, as documented by Yao *et al.* [35] and Feng *et al.* [45]. The greater magnitude of Δb relative to Δa indicates higher sensitivity of the yellow-blue axis to UV-C-induced photochemical reactions. ΔE provides an integrated assessment of total colour variation by combining the contributions of ΔL , Δa , and Δb into a single perceptual parameter. One-way ANOVA demonstrated a highly significant effect of UV-C dose on ΔE ($p < 0.000001$), confirming a strong treatment-dependent response. All irradiated samples exhibited ΔE values of

approximately 4.0 - 5.1, whereas the control remained at 0. Given that ΔE values above 2.0 are generally perceptible and those exceeding 3.0 represent a distinct colour change, the results indicate that UV-C irradiation induces a statistically significant and visually discernible modification of sedge surfaces.

Tensile strength

Figure 5 and **Table 3** collectively illustrate the evolution of the mechanical behavior of grey sedge fiber surfaces subjected to UV-C irradiation over treatment times of 10 - 50 min. The stress-strain curves (**Figure 5**) exhibit a characteristic elastic-plastic deformation prior to failure, typical of lignocellulosic plant-based fibers in which load transfer is governed by microfibrillar alignment and interfacial bonding among structural polymers [29]. Accordingly, the untreated grey sedge fibers displayed a tensile strength of 83.2 ± 17.3 MPa and an elongation at break of $3.9 \pm 0.5\%$, reflecting the inherent mechanical performance of grey sedge fibers composed of cellulose microfibrils embedded within a lignin-hemicellulose matrix. This baseline mechanical response is consistent with established fiber mechanics for untreated lignocellulosic materials, in which hydrogen-bonded networks and microstructural orientation dominate deformation and failure behavior [45,46].

Following 10 min of UV-C irradiation ($1,438 \pm 11$ mJ/cm²), a slight reduction in tensile strength (75.9 ± 22.8 MPa) was observed compared with the control, while elongation at break remained essentially unchanged; however, given the relatively large standard deviation, this difference appears modest and within experimental variability. These results suggest that

short-duration UV-C exposure primarily affects surface chemistry with limited impact on bulk mechanical integrity, thereby preserving the overall elastic-plastic deformation behavior, consistent with reports on UV-treated lignocellulosic materials where initial irradiation modifies surface functional groups without substantially disrupting internal cellulose networks [36,38,45]. With increasing exposure time, more pronounced mechanical degradation was observed, as tensile strength decreased to 58.5 ± 11.4 MPa at 20 min ($2,876 \pm 23$ mJ/cm²), accompanied by a slight reduction in elongation at break and earlier fracture in the stress–strain curves, behavior consistent with progressive UV-induced degradation processes such as photo-oxidation and potential chain scission within lignocellulosic components. At intermediate exposure times of 30 - 40 min ($4,314 \pm 34$ mJ/cm² - $5,752 \pm 45$ mJ/cm²), tensile strength values (66.5 - 68.6 MPa) were higher than those at 20 min; however, considering the overlapping standard deviations and limited sample size ($n = 3$), this apparent increase should be interpreted cautiously and may reflect experimental variability rather than a definitive structural recovery. Overall, the mechanical response under UV-C irradiation demonstrates a dose-dependent but non-linear trend, likely governed by progressive degradation processes, with intermediate fluctuations falling within the range of experimental uncertainty.

At the longest irradiation time of 50 min ($7,191$ mJ/cm²), the tensile strength declined again to 62.1 ± 1.3 MPa, while elongation at break decreased to $3.5 \pm 0.3\%$, indicating cumulative UV-C-induced damage and progressive embrittlement of the fiber structure. Therefore, the mechanical behavior of grey sedge under UV-C irradiation demonstrates a dose-dependent but non-linear response, governed by competing surface modification and bulk degradation processes. In contrast

to polymer-based protective strategies, such as P(VDF-HFP) coatings, which enhance tensile strength by forming a durable reinforcing layer [19], UV-C treatment does not mechanically reinforce the fibers. Nevertheless, the present results confirm that UV-C doses sufficient for antifungal control can be achieved with only moderate mechanical degradation, provided that the exposure time is carefully optimized. This finding supports UV-C irradiation as a viable, chemical-free preservation strategy for grey sedge products.

To ensure consistency with the statistical analysis applied to fungal coverage, a one-way ANOVA was conducted to evaluate the effect of UV-C irradiation on the tensile strength and elongation at break of grey sedge fibers. The results revealed no statistically significant differences among the treatment groups for tensile strength ($F = 1.10$, $p = 0.410 > 0.05$, $F < F_{\text{crit}} = 3.11$) or elongation at break ($F = 1.62$, $p = 0.228 > 0.05$), indicating that the observed variations fall within experimental uncertainty. Although a general decreasing trend in tensile strength was noted with increasing UV-C dose, particularly at intermediate exposure times, the substantial standard deviations and overlap among groups suggest that these changes are not statistically distinguishable. This is further supported by the relatively high within-group variance ($MS_{\text{within}} = 224.95$), which reflects the intrinsic heterogeneity of lignocellulosic fibers and the limited sample size ($n = 3$). Overall, these findings demonstrate that UV-C irradiation, within the investigated dose range, does not significantly alter the mechanical properties of grey sedge fibers, in contrast to its pronounced and statistically significant effect on fungal suppression, thereby confirming its suitability as a non-destructive preservation strategy.

Table 3 Tensile strength and elongation at break of grey sedge (*Lepironia articulata*) fibers after UV-C irradiation at different exposure times and doses. Values are expressed as mean $\pm$ SD.

UV-C exposure time (min)	UV-C dose (mJ/cm ²)	Tensile strength (MPa)	Elongation at break (%)
0 (Control)	0	83.2 ± 17.3	3.9 ± 0.5
10	$1,438 \pm 11$	75.9 ± 22.8	3.9 ± 0.2
20	$2,876 \pm 23$	58.5 ± 11.4	3.5 ± 0.6
30	$4,314 \pm 34$	66.5 ± 17.3	4.3 ± 0.1
40	$5,752 \pm 45$	68.6 ± 10.1	3.6 ± 0.5
50	$7,191 \pm 57$	62.1 ± 1.3	3.5 ± 0.3

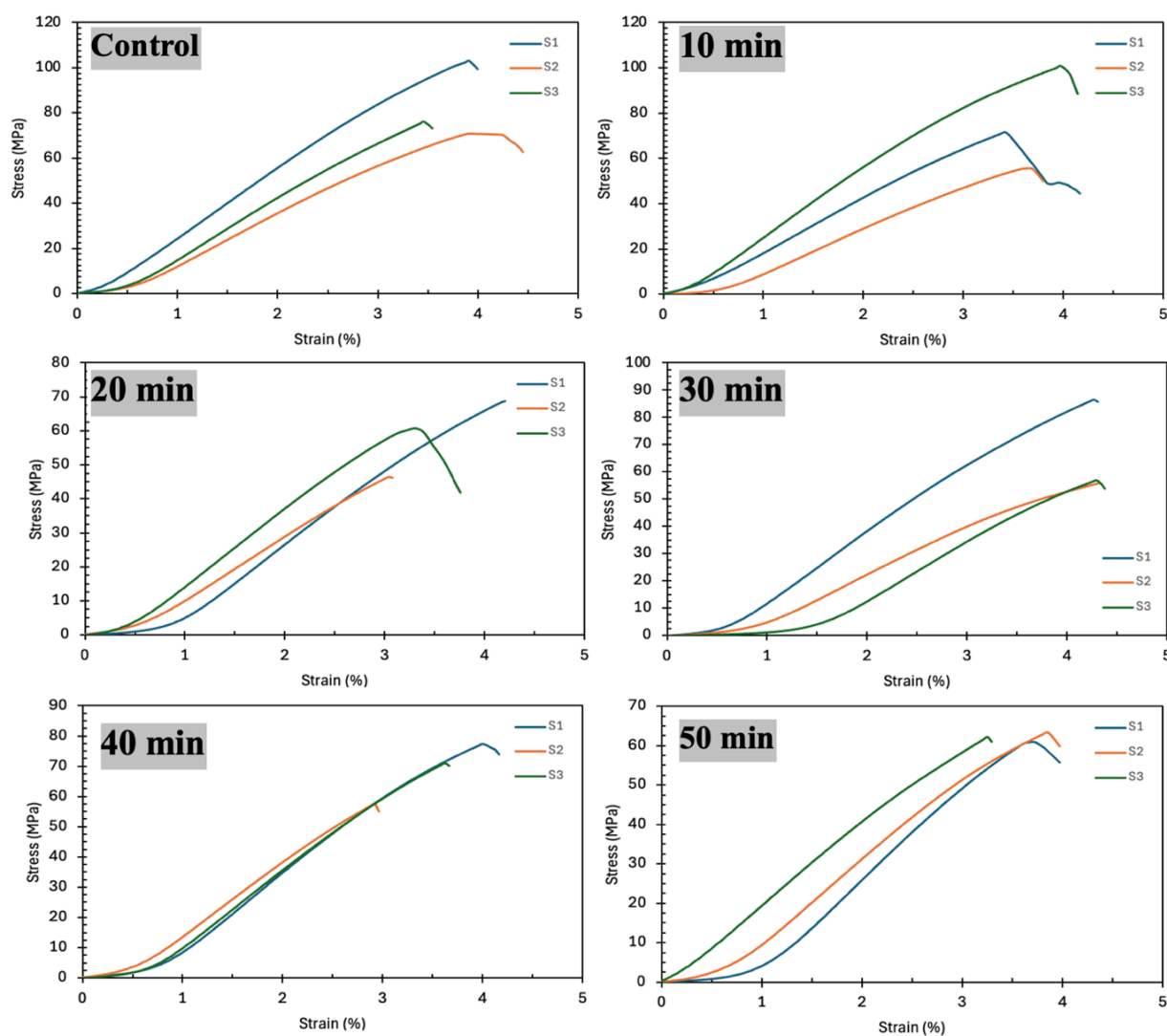


Figure 5 Stress-strain curves of grey sedge fibers under UV-C irradiation at different exposure times (0 - 50 min, corresponding to 0 - 7,191 mJ/cm²). The control (untreated) sample is compared with irradiated samples, with 3 replicates (S1 - S3) shown for each condition. All samples exhibit typical elastic-plastic deformation followed by fracture. UV-C treatment generally leads to a reduction in tensile strength with increasing exposure time, although variability among replicates is evident. Overall, the results indicate a dose-dependent but non-linear effect of UV-C irradiation on mechanical behavior within experimental scatter.

Antifungal performance of UV-C treatment against *Trichoderma* sp.

The antifungal performance of the custom-built UV-C irradiation chamber against *Trichoderma* sp. on grey sedge fiber surfaces was evaluated at UV-C doses of 575.3 ± 4.6 mJ/cm², $1,150.6 \pm 9.1$ mJ/cm², $1,725.8 \pm 13.7$ mJ/cm², $2,301.1 \pm 18.2$ mJ/cm², and $2,876.4 \pm 22.8$ mJ/cm². Notably, these dosage levels were selected as they fall within a range that maintains the physical and mechanical properties of the grey sedge fibers within acceptable limits. The relative humidity during the

experiment ranged from 69% to 74%. Additionally, the temperature at the UV-C sample position ranged from 28.6 to 33.4 °C, with a mean value of 30.8 ± 1.5 °C. Although temperature is a key factor influencing fungal growth, this range falls within the commonly reported optimal growth temperatures for *Trichoderma*, which generally span 25 - 30 °C and can extend up to approximately 32 - 35 °C for some isolates without significant growth suppression [42,43]. Studies on multiple *Trichoderma* isolates found that mycelial growth rates were highest around 24.5 - 29.4 °C and

remained robust at temperatures near 30 °C, with only higher temperatures above this range causing marked reductions in growth or activity [44]. Therefore, the observed temperature range during UV-C irradiation is unlikely to have independently inhibited *Trichoderma* growth, supporting the interpretation that UV-C exposure itself (rather than modest temperature increases) was the primary factor affecting fungal viability.

Fungal development was monitored by digital photography at 8-hour intervals throughout the

incubation period. Representative images recorded at 24, 48, 56, 64, and 72 h after irradiation are shown in **Figure 6**. In addition, a quantitative analysis of fungal growth was conducted by measuring the fungal coverage area on the culture plates using ImageJ. For each condition, 3 independent samples were tested, and the average coverage was calculated. These findings are summarized in **Table 4**, consistent with the visual observations in **Figure 6**.

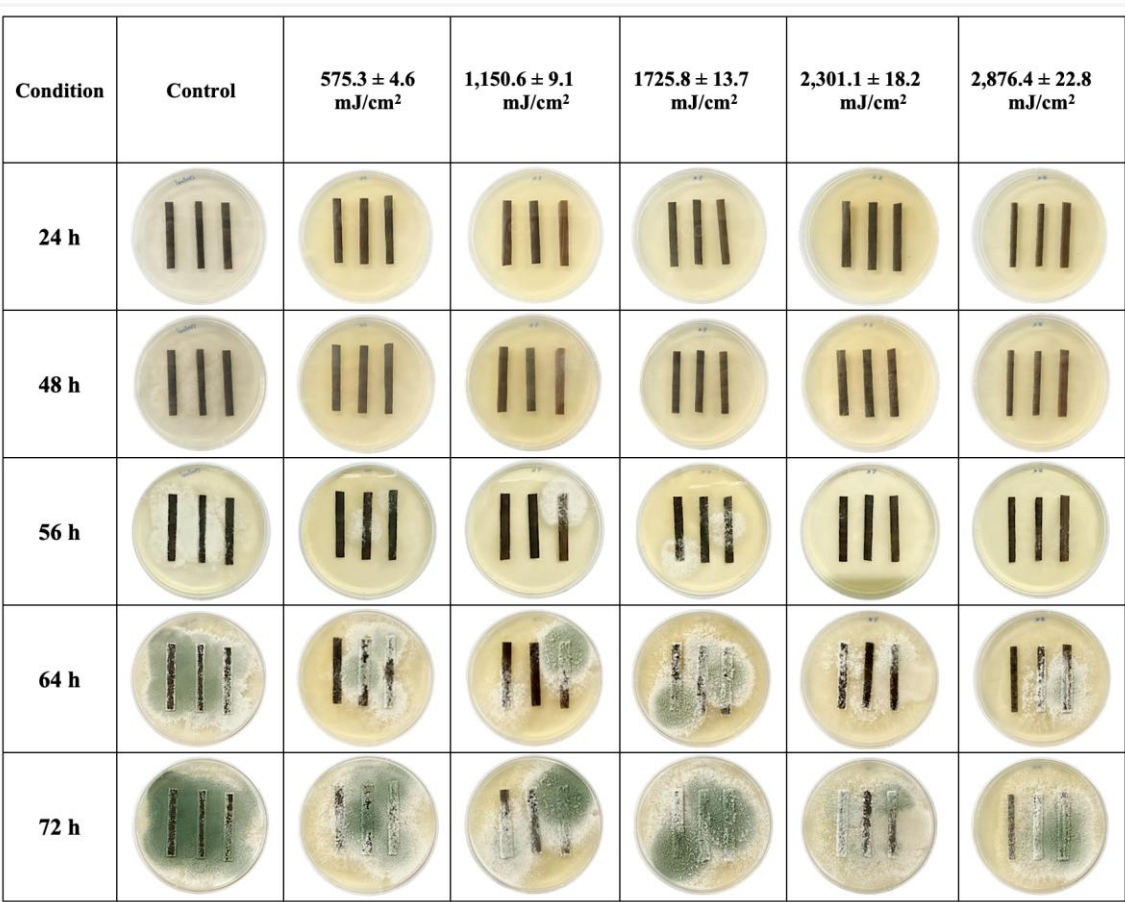


Figure 6 Representative digital images showing the growth progression of *Trichoderma* sp. on grey sedge surfaces following UV-C irradiation at doses of 575.3 ± 4.6 mJ/cm², 1,150.6 ± 9.1 mJ/cm², 1,725.8 ± 13.7 mJ/cm², 2,301.1 ± 18.2 mJ/cm², and 2,876.4 ± 22.8 mJ/cm². Images were recorded at 24, 48, 56, 64, and 72 h to illustrate the time-dependent development of fungal colonies under different UV-C treatment conditions.

Table 4 Comparative evaluation of *Trichoderma* sp. growth on grey sedge fiber surfaces after UV-C irradiation.

UV-C dose (mJ/cm ²)	% Fungal coverage (24 h)	% Fungal coverage (48 h)	% Fungal coverage (56 h)	% Fungal coverage (64 h)	% Fungal coverage (72 h)
0 (Control)	6.21 ± 0.48	27.09 ± 0.92	37.86 ± 1.30	58.01 ± 1.61	87.97 ± 1.47
575.3 ± 4.6	0.00 ± 0.00	6.22 ± 0.52	37.57 ± 1.96	41.28 ± 0.65	61.72 ± 1.32

UV-C dose (mJ/cm ²)	% Fungal coverage (24 h)	% Fungal coverage (48 h)	% Fungal coverage (56 h)	% Fungal coverage (64 h)	% Fungal coverage (72 h)
1,150.6 ± 9.1	0.00 ± 0.00	9.00 ± 0.30	11.72 ± 0.88	35.55 ± 0.75	68.84 ± 1.87
1,725.8 ± 13.7	0.00 ± 0.00	2.89 ± 0.81	17.70 ± 1.57	50.06 ± 0.86	67.04 ± 2.00
2,301.1 ± 18.2	0.00 ± 0.00	5.10 ± 0.81	9.16 ± 1.57	30.05 ± 0.85	56.56 ± 5.96
2,876.4 ± 22.8	0.00 ± 0.00	0.00 ± 0.00	4.68 ± 0.61	24.98 ± 1.77	55.47 ± 1.77

In the control group (0 mJ/cm²), rapid and consistent mycelial growth of *Trichoderma sp.* was observed (**Figure 6; Table 4**), with visible development within 24 - 48 h and surface coverage increasing from $6.21 \pm 0.48\%$ to $27.09 \pm 0.92\%$. By 72 h, dense and nearly uniform colonization was achieved ($87.97 \pm 1.47\%$), indicating favorable conditions for fungal proliferation in the absence of inhibitory factors. In contrast, UV-C-treated samples exhibited a clear dose-dependent suppression of growth. At lower doses (575.3 ± 4.6 mJ/cm² - $1,150.6 \pm 9.1$ mJ/cm²), mycelial development was delayed but still evident at later stages. Moderate doses ($1,725.8 \pm 13.7$ mJ/cm² - $2,301.1 \pm 18.2$ mJ/cm²) markedly reduced both growth rate and coverage, while higher doses ($\geq 2,876.4 \pm 22.8$ mJ/cm²) produced the strongest suppression, although complete eradication was not achieved.

The delayed mycelial development observed in UV-C-treated samples is primarily attributed to molecular damage induced by UV-C irradiation. UV-C photons generate pyrimidine dimers in DNA, disrupting its structure and inhibiting essential processes such as replication and transcription. As a result, conidial germination is suppressed and hyphal growth is delayed. In contrast, the control group retains intact DNA, enabling rapid mycelial expansion within 48 h. This mechanism is consistent with previous reports indicating that UV-C inactivates *Trichoderma* by impairing genetic material rather than causing immediate cell death [23]. Supporting evidence further shows that light-responsive pathways in *Trichoderma atroviride* are closely linked to DNA repair systems, and excessive UV-induced damage beyond repair capacity significantly delays or inhibits growth [48].

A clear dose-dependent delay in fungal emergence was observed at 56 h. Growth was detectable only at lower UV-C doses (575.3 ± 4.6 mJ/cm² to $1,725.8 \pm 13.7$ mJ/cm²), while colonies at higher doses ($\geq 2,301.1 \pm$

18.2 mJ/cm²) remained barely visible. This pattern may reflect increasing DNA damage with dose, which inhibits conidial germination and early hyphal development. At moderate doses, partial recovery allows delayed growth, whereas at higher doses, damage exceeds repair capacity, resulting in near-complete suppression. These observations are strongly supported by statistical analysis, which revealed a highly significant effect of UV-C treatment on fungal growth (one-way ANOVA, $F = 330.99$, $p < 0.001$), confirming a clear dose-dependent reduction. Similar dose-dependent inhibition has been reported in several fungi, including *Trichoderma asperellum*, where higher UV-C doses significantly reduce spore germination and early growth [22,24,41].

Despite this initial inhibition, rapid fungal development was observed after 64 h in both control and treated groups. Colonies transitioned from white mycelia to green pigmentation, indicating active sporulation. This recovery suggests that surviving conidia were able to repair or tolerate UV-induced damage and resume growth. The white-to-green transition is characteristic of *Trichoderma*, reflecting conidia formation during maturation [49]. The ability to regain growth after UV exposure highlights the species' efficient DNA repair mechanisms and environmental resilience, enabling eventual proliferation comparable to that of untreated samples [44,48].

However, although high UV-C doses significantly reduced *Trichoderma sp.* viability on grey sedge fibers, residual fungal growth was still observed in some samples. This incomplete inhibition can be attributed to several microbiological and physical factors, including the efficiency of UV-C on complex surfaces.

First, sublethal UV-C exposure can trigger stress responses in fungal cells, leading to structural adaptations that help them retain some viability. This aligns with findings showing that insufficient UV-C

exposure causes the development of more resistant mycelial structures that can protect live spores beneath surface layers. As a result, these spores can survive and regrow even after exposure to high UV-C doses. [39]. On complex, fibrous substrates like sedge, surface irregularities and fiber porosity can create micro-shadowed regions that block uniform irradiation, allowing some spores to avoid direct UV-C exposure and stay viable. Similar “shadowing” effects have been documented in surface UV-C applications where clumped cells or structural irregularities reduce effective UV dose received by all microbial targets [40].

Second, *Trichoderma* sp. exhibits intrinsic variability in UV susceptibility, even when spore germination is markedly reduced by UV-C, a fraction of spores may remain intact and capable of growth if not fully inactivated. These observations are consistent with results showing that UV-C treatment is more effective against spore germination than against established mycelial structures, suggesting that spores embedded within surface features or microenvironments may survive conditions lethal to free spores [26,40,41].

Together, these factors highlight that complete eradication of fungal viability on complex natural surfaces may require either higher doses, longer exposure times, or combined strategies (e.g., UV-C plus chemical or physical disruption) to overcome shadowing and sublethal protection mechanisms. Nevertheless, the overall suppression observed aligns with the documented effectiveness of UV-C in reducing fungal loads, even if complete inhibition is not always achieved under practical irradiation conditions—emphasizing the need for comprehensive treatment design in applied disinfection studies.

Overall, these findings demonstrate that while UV-C irradiation markedly suppresses *Trichoderma* sp. growth on grey sedge fibers, complete fungal inactivation is constrained by substrate complexity and biological resistance mechanisms. The observed reduction in fungal viability confirms the effectiveness of UV-C as a non-chemical intervention, yet also underscores the importance of irradiation geometry, dose uniformity, and exposure conditions when applied to natural fibrous materials. These considerations provide a critical basis for interpreting the practical efficacy of the developed UV-C system and inform strategies for optimizing treatment conditions.

Optimization and practical implications of UV-C treatment

The present results demonstrate a clear dose-dependent trade-off between antifungal effectiveness and material modification of grey sedge fibers. Lower UV-C doses (575.3 ± 4.6 mJ/cm² - $1,150.6 \pm 9.1$ mJ/cm²) only delayed the growth of *Trichoderma* sp., while moderate doses ($1,725.8 \pm 13.7$ mJ/cm² - $2,301.1 \pm 18.2$ mJ/cm²) substantially reduced both the rate and spatial extent of fungal colonization. Higher doses ($> 2,876.4 \pm 22.8$ mJ/cm²) provided the strongest suppression but did not achieve complete fungal eradication. When these biological responses are considered together with the material properties, a practical optimization framework can be established. UV-C exposure within the tested range ($1,438 \pm 11$ mJ/cm² - $7,191 \pm 57$ mJ/cm²) resulted in visually perceptible color changes ($\Delta E \approx 4.0 - 5.1$), whereas tensile properties showed a gradual degradation trend and surface wettability remained largely unchanged. Based on these combined observations, the UV-C dose range of approximately 1,700 - 2,300 mJ/cm² was identified as the optimal treatment window, providing the best balance between antifungal efficacy and preservation of grey sedge fiber properties. Within this range, fungal growth was effectively suppressed, while the mechanical integrity and surface characteristics of the fibers were largely maintained. In contrast, lower doses ($< 1,700$ mJ/cm²) showed insufficient antifungal performance, whereas higher doses ($> 2,300$ mJ/cm²) resulted in more pronounced changes in fiber properties, potentially compromising material quality and practical usability.

Although this study focused on grey sedge fibers and *Trichoderma* sp., the underlying antimicrobial mechanism of UV-C irradiation—primarily DNA photodamage and oxidative stress—suggests that similar approaches may be applicable to other lignocellulosic natural fibers and fungal contaminants. However, the optimal treatment conditions may vary depending on fiber composition, surface morphology, and fungal species sensitivity. Future work should therefore evaluate the applicability of UV-C treatment to a wider range of plant-based materials and fungal pathogens, as well as investigate large-scale treatment configurations and long-term material durability. Within the identified optimal dose range, UV-C irradiation

represents a promising chemical-free preservation strategy that could be feasibly implemented in artisanal or small-scale industries for protecting natural fiber products from fungal contamination.

Conclusions

This study highlights essential design principles for UV-C treatment of natural fiber products: ensure uniform irradiation through symmetrical lamp placement and reflective interior design, map the spatial dose distribution during setup, and consider surface topography when setting treatment parameters. For practical applications, cost-effective UV-C systems should include adjustable exposure controls, simple fixtures to minimize shadowing (such as rotating or tumbling holders and reflective liners), and regular monitoring of environmental conditions and irradiance to maintain consistent performance in small-scale operations. UV-C treatment can greatly reduce fungal loads on grey sedge without chemicals, but it should be combined with additional measures like clean storage, moisture control, and targeted mechanical handling to access shadowed micro-sites and achieve more thorough control. By offering a customized, low-impact approach along with practical system design and operational recommendations, this work promotes sustainable preservation of grey sedge products by reducing reliance on chemicals and enabling scalable, resource-efficient fungal management.

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Declaration of Generative AI in Scientific Writing

The authors used ChatGPT (OpenAI) to assist with language refinement and clarity of the manuscript. Grammarly was also used to check grammar and improve the overall readability. All scientific

interpretations and final manuscript revisions were performed by the authors.

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