Design and Digital-Twin Simulation of a Wearable RGB Optical-Fibre-Embedded Smart T-Shirt: A MATLAB-Based Photonic and Interactive Visualisation Framework

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DOI: https://doi.org/10.47772/IJRISS.2026.100701114

Received: 07 August 2026; Accepted: 12 August 2026; Published: 21 August 2026

ABSTRACT

This paper presents a computational proof-of-concept and pre-fabrication design framework—not a validated digital twin of a physical garment—for an RGB optical-fibre smart T-shirt. Twelve polymer optical fibres are placed in a serpentine layout on a parametric three-dimensional T-shirt surface and powered by one light-emitting diode through a one-to-twelve splitter. A MATLAB model combines total internal reflection, Beer–Lambert loss, macro-bend loss and fabric-stretch loss inside an interactive interface. The user can change wavelength and intensity while a light pulse moves along the fibres; the animation can be saved as video. The simulation recovers the expected qualitative colour trend (red fades least, blue fades most) under illustrative attenuation coefficients and produces a stable, controllable animation. An expanded sensitivity analysis shows that distal brightness is most sensitive to the bulk attenuation coefficient and fibre length, moderately sensitive to splitter efficiency and bend parameters, and only weakly sensitive to the stretch coefficient under the tested ranges. All loss coefficients remain illustrative; results demonstrate design-tool behaviour rather than measured performance. Designers can compare source colours, locate high-curvature zones and estimate splitter power needs before physical sampling. A measurement protocol and pre-registered validation design are supplied for future laboratory work. The framework unifies garment-level fibre routing, splitter power budgeting and multi-mechanism optical loss in one interactive environment—an integration not previously reported as a complete pre-fabrication tool for wearable photonic textiles.

Keywords: Smart textiles, Wearable photonic garments, Polymer optical fibre, Digital twin, Pre-fabrication design, Bend loss

INTRODUCTION

Over the last twenty years, garments that carry optical fibres in the fabric—often called wearable photonic textiles—have grown into a distinct branch of smart clothing. Designers use them for illuminated fashion, quiet health sensing and light-based therapy. Polymer optical fibres (POFs) suit this role well: they bend easily, weigh little, cost relatively little and do not suffer from electromagnetic interference. They can also be woven or knitted with ordinary textile machines [1].

Two main uses appear in the literature. Sensing textiles change the guided light through bending, intensity shifts or Bragg gratings and thereby report strain, pressure or body signals [2], [3]. Illuminating textiles deliberately leak light sideways—by notching the cladding, texturing the surface or controlled bending—so that the fibre glows for fashion, safety or therapy [1], [4], [5]. Wider e-textile work has moved quickly as well. Recent reviews cover sensory interactive fibres [6], fibre-shaped electronics [7] and human-centred, Internet-of-Things-linked smart textile design [8]. Smart textiles are also discussed as digital-human interfaces in metaverse settings [9]. Durability and wash resistance remain practical obstacles [10]. Outside pure fibre optics, Jacquard-woven photonic-bandgap displays [11] and visible-light-communication fashion accessories [12] show other paths to fabric-integrated light.

Despite this progress, garment-level design is still typically validated only after physical integration of fibre into cloth. Relatively few studies report an end-to-end computational framework that lets a designer evaluate fibre routing, splitter power budget and expected colour or intensity behaviour on a full garment geometry before fabrication. Digital-twin methods are gaining attention in the wider textile sector as a way to reduce prototype waste [13], yet their application to garment-level photonic subsystems remains limited. This paper addresses that gap with a MATLAB-based computational proof-of-concept and pre-fabrication design framework for a twelve-channel RGB optical-fibre smart T-shirt. The work is deliberately scoped as a design tool: it is not claimed to be a calibrated digital twin of any specific physical garment.

The model places the fibre network on a parametric, body-shaped garment surface, routes each fibre along a serpentine path that follows the chest curve, and combines four loss mechanisms—total internal reflection, Beer–Lambert bulk attenuation, curvature-dependent macro-bend loss and stretch-induced loss—into a frame-by-frame view of the moving light pulse. An interactive interface exposes wavelength, intensity and playback-speed controls, and the animation can be exported as video for design documentation.

The remainder of the paper is organised as follows. Section 2 reviews related work systematically and positions the contribution against prior garment- and fibre-level studies. Section 3 describes the system design, mathematical assumptions and parameter-selection rationale. Section 4 presents results, including an expanded sensitivity analysis. Section 5 states limitations. Section 6 sets out a recommended physical evaluation protocol, and Section 7 concludes.

Related Work

Gong et al. [1] provide a comprehensive review of wearable fibre-optic technology in smart textiles, covering fashion illumination, phototherapy and vital-sign monitoring, together with side-emission, wavelength-modulation and intensity-modulation mechanisms and weaving or knitting integration routes. Selm et al. [5] review polymeric optical-fibre fabrics for illumination and sensing, including plain-weave integration and laser-ablation notching for local emission control. These reviews establish the application landscape but do not present garment-level computational design tools.

On the sensing side, Rothmaier et al. [3] demonstrated a textile pressure sensor based on bend-induced transmission loss in flexible plastic optical fibres. Grillet et al. [2] embedded macro-bend, Bragg-grating and time-domain fibre sensors in medical textiles for respiratory monitoring. Peters [14] reviews polymer optical-fibre sensors more broadly. Losada et al. [15] measured attenuation and mode diffusion under small-radius curvatures in POF, supporting exponential curvature–loss relationships used in macro-bend models. These works validate physical sensing mechanisms on fabric or fibre samples; they do not offer pre-fabrication simulation of a full illuminated garment.

On the source and coupling side, Lanziano et al. [16] report a measured one-to-eight multicore polycarbonate POF splitter with experimental insertion-loss data that help bound the simplified splitter efficiency used here. Wu et al. [17] address multi-wavelength source engineering against eye-safety and colour-rendering criteria. Cuevas et al. [18] illustrate the maturity of interactive MATLAB graphical interfaces as engineering design tools. Sayed et al. [11] demonstrated Jacquard-woven photonic-bandgap fibre displays with dynamic colour control through the weave—an alternative, loom-integrated route rather than discrete serpentine fibre routing. Comfort and durability remain open challenges for e-textiles generally [10], [19], [20].

Angelova [13] argues for digital twins across the textile industry to support sustainable design and reduced prototyping waste, but does not implement a garment-level photonic digital twin. Across this body of work, the dominant validation path remains empirical testing of physical prototypes. A systematic reading of the cited literature indicates that end-to-end computational frameworks combining (i) parametric full-garment geometry,

(ii) multi-channel serpentine fibre routing, (iii) splitter power budgeting, (iv) multi-mechanism optical loss and (v) real-time interactive visualisation have not previously been reported as an integrated pre-fabrication design tool for wearable photonic textiles. The present framework targets that specific gap. Table 1 summarises the positioning.

Table 1. Positioning of the present framework against representative prior work.

Study / focus	**Garment geometry**	**Multi-loss optical model**	**Interactive design tool**	**Physical validation**
Gong et al. [1] (review)	—	—	—	Review
Selm et al. [5] (POF fabrics)	Fabric level	Partial	No	Reported in field
Rothmaier / Grillet [2],[3]	Textile sample	Bend/strain	No	Yes
Sayed et al. [11] (Jacquard)	Woven display	Bandgap optics	No	Yes
Angelova [13] (textile DT)	Industry-level	—	Conceptual	—
This work (pre-fab framework)	Full T-shirt	TIR+Beer+bend+stretch	Yes (MATLAB GUI)	Protocol only

SYSTEM DESIGN AND METHODOLOGY

Overview of the Smart-Fibre Garment Architecture

The simulated system has five functional stages (Figure 1): (i) a single light-emitting diode near the left shoulder; (ii) a one-to-twelve optical splitter; (iii) twelve polymer optical-fibre channels routed in a serpentine path across the chest; (iv) a light-transport and loss model that updates pulse position, colour and intensity each frame; and (v) an interactive control layer for wavelength, intensity and playback speed. The architecture is intended as a pre-fabrication design sandbox, not as a calibrated replica of a manufactured product.

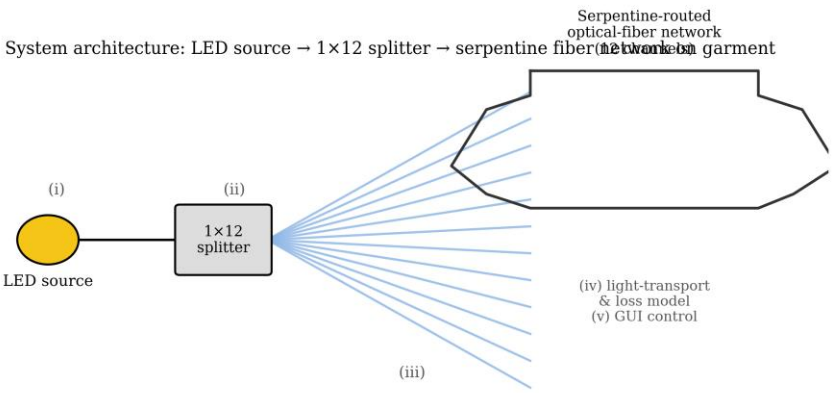

Figure 1. System architecture: LED source, 1×12 splitter, and twelve serpentine fibre channels on the parametric garment surface.

Parametric Three-Dimensional Garment Substrate Model

The garment surface is built on a regular (x, y) mesh of 220 × 260 samples. A chest curvature term $z(x) = 2\cdot\cos^2(x/12)$ gives a forward bulge. Boolean masks add torso, sleeves and shoulders and remove an elliptical neckline; exterior points are set to NaN so that only the garment is drawn. Silhouette parameters can be changed without rewriting the optical model.

Optical Source and Splitter Network

A single diode feeds a one-to-twelve splitter. Power per fibre follows $P\_fibre = \eta \cdot P\_in / N$, with $N = 12$ and $\eta = 0.90$ as an illustrative insertion efficiency, bounded at 0.80–0.95 following measured 1×N POF splitter excess-loss ranges [16]. Wavelength- and port-dependent excess loss is not resolved in this first-order budget.

Serpentine Fibre-Routing Path Generation

Each fibre has a baseline row across the chest (4 cm spacing) and a serpentine lateral offset of amplitude 1.2 cm with four oscillations along a 34 cm path that also follows chest curvature. Fibres are drawn as concentric core and cladding tubes for visualisation. Core and cladding radii used for rendering (0.12 cm and 0.25 cm) are illustrative display scales, not claims of physical POF dimensions.

Photonic Transport Model and Mathematical Assumptions

Light confinement is checked against total internal reflection. For a step-index fibre, $\theta\_c = \sin^{-1}(n\_clad / n\_core)$. Representative indices $n\_core \approx 1.49$ and $n\_clad \approx 1.41$ (typical of PMMA-core / fluorinated-cladding POF systems reviewed by Peters [14] and Gong et al. [1]) give $\theta\_c \approx 71°$. A two-dimensional ray-bounce simulation recovers the expected zig-zag guided path (Figure 2). The travelling field is represented as $I\_wave(d, t) = 0.5\cdot[1 + \cos(k\cdot d - \omega\cdot t)]$ with $k = 2\pi/\lambda$ and $\omega = 2\pi v/\lambda$, $v = c/n$, solely to give the animation a wave-like appearance.

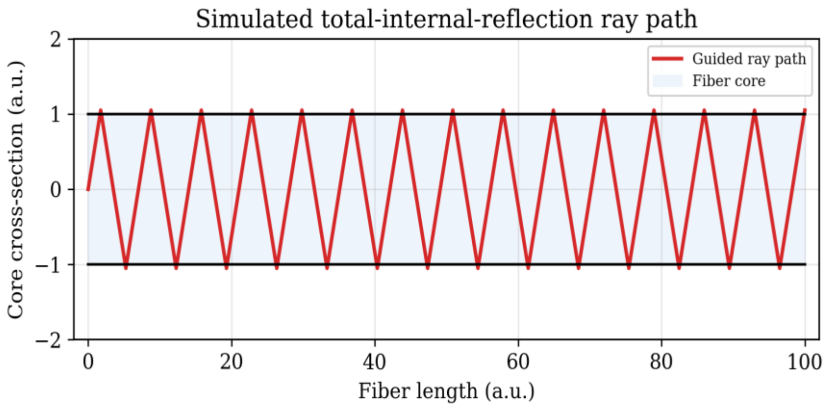

Figure 2. Simulated total-internal-reflection ray path along the fibre core.

Attenuation, Bend-Loss and Fabric-Deformation Loss Models

Three multiplicative loss terms set local intensity. Bulk (Beer–Lambert) attenuation is $A(d) = \exp(-\alpha\cdot d)$ over normalised length $d \in [0,1]$. Macro-bend loss uses path curvature κ from numerical differentiation of the fibre path, with $B(\kappa) = \exp(-\beta\cdot\kappa)$. Fabric-stretch loss is $S(\varepsilon) = \exp(-s\cdot|\varepsilon|)$. Instantaneous intensity combines these with the travelling-wave term.

Parameter-selection rationale for the illustrative attenuation coefficients. The values $\alpha\_blue = 3.1$, $\alpha\_green = 2.2$ and $\alpha\_red = 1.5$ (dimensionless over normalised length) were chosen to demonstrate a qualitative Rayleigh-like ordering in which short-wavelength (blue) loss exceeds mid-visible (green) loss, which in turn exceeds longer-wavelength (red) loss in the visible window of typical PMMA-based POF [14], [15]. They are not fitted to a specific commercial fibre datasheet. Real spectral attenuation also includes CH-absorption features that can raise loss toward the red–near-infrared; therefore the ordering is instructional for relative colour behaviour in the design tool, not a prediction for any named product. Once measured attenuation in dB/m is available, conversion $\alpha\_dB/m = 4.343 \times \alpha / L$ (L in metres) should replace these illustrative values.

The bend-loss prefactor $\beta = 4$ is likewise illustrative: it is set so that serpentine turning points produce visible local dimming in the animation. It should be recalibrated to mandrel-wrap data of the intended fibre, following the exponential curvature–loss relationship reported by Losada et al. [15].

Correspondence of the fabric-stretch variable to realistic garment deformation. The deformation parameter ε is a dimensionless time-varying quantity, implemented as a slow sinusoid of amplitude 0.10. In physical terms this amplitude is intended to represent on the order of 10% cyclic fabric elongation—consistent with moderate torso stretch of a knitted T-shirt during wear (reaching, breathing, arm motion)—rather than extreme athletic elongation. The stretch-loss scale s = 0.3 is an illustrative sensitivity coefficient reflecting the known strain dependence of POF transmission [3], [14]. The mapping is deliberately simplified: it does not resolve local yarn-level strain fields, hysteresis or permanent set. Its role is to show designers that mechanical deformation can modulate brightness, not to predict laboratory strain–loss curves.

Interactive Control and Wavelength Mapping

Table 2 lists the wavelength-to-colour mapping and illustrative attenuation coefficients. The interface provides discrete colour buttons and continuous intensity and speed controls.

Table 2. Wavelength-to-colour mapping and illustrative attenuation coefficients.

Source	Wavelength (nm)	RGB	α (a.u., illustrative)
Blue	450	(0,0,1)	3.1
Green	532	(0,1,0)	2.2
Red	650	(1,0,0)	1.5
White	—	(1,1,1)	n/a

Simulation and Video-Export Pipeline

Static geometry is drawn once; a 300-frame loop updates fibre colour, deformation and glow markers. Frames can be exported to MPEG-4 via VideoWriter for design review without a live MATLAB session.

RESULTS AND DISCUSSION

Static Geometric Rendering and TIR Check

The parametric garment, diode, splitter fan-out and twelve serpentine fibres render as a coherent three-dimensional T-shirt (Figure 3). The independent ray-bounce simulation recovers a stable zig-zag path consistent with guidance above the critical angle (Figure 2).

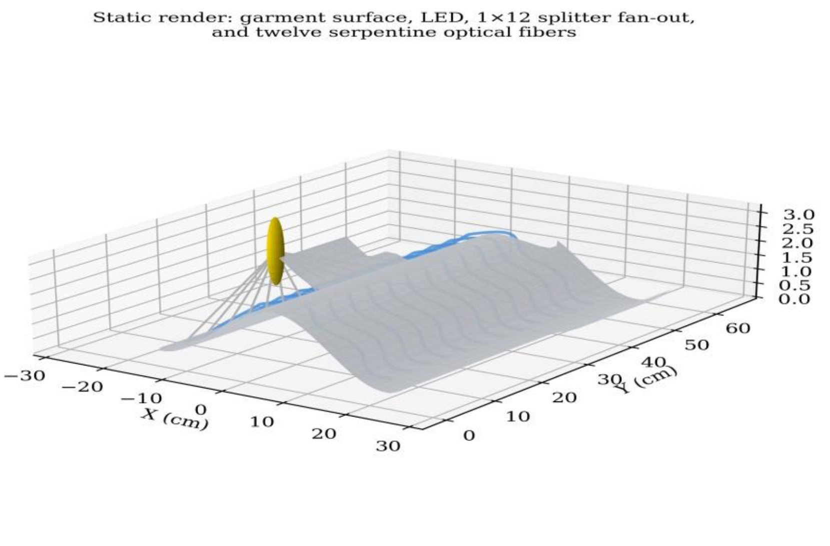

Figure 3. Static render of the complete garment model.

Wavelength-Dependent Attenuation Comparison

Under the illustrative coefficients in Table 2, normalised intensity versus length shows red fading least and blue most (Figure 4), consistent with a Rayleigh-dominated short-wavelength trend in the visible for typical PMMA POF [14], [15]. This comparison is a design-tool demonstration of relative colour behaviour, not a spectral prediction for a named commercial fibre.

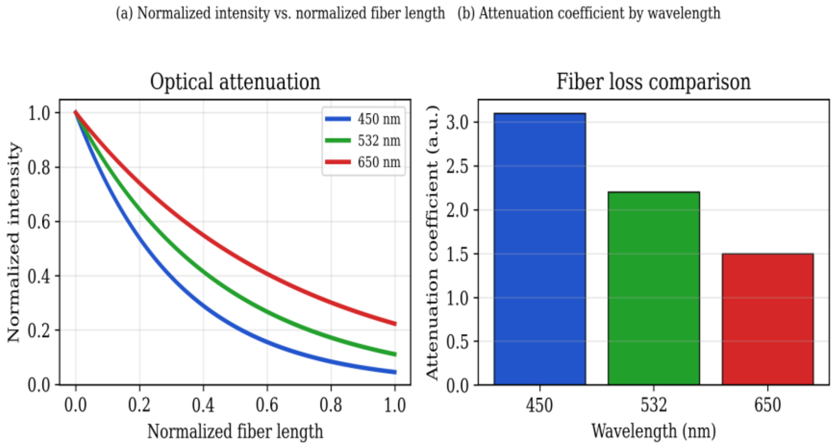

Figure 4. Illustrative normalised intensity versus normalised fibre length for 450, 532 and 650 nm.

Dynamic Animation and Interactive Control

The combined intensity model produces a moving trailing pulse with local dimming at high-curvature serpentine turns and slow global modulation from the stretch term (Figure 5). Interface changes update colours in real time without restarting the loop.

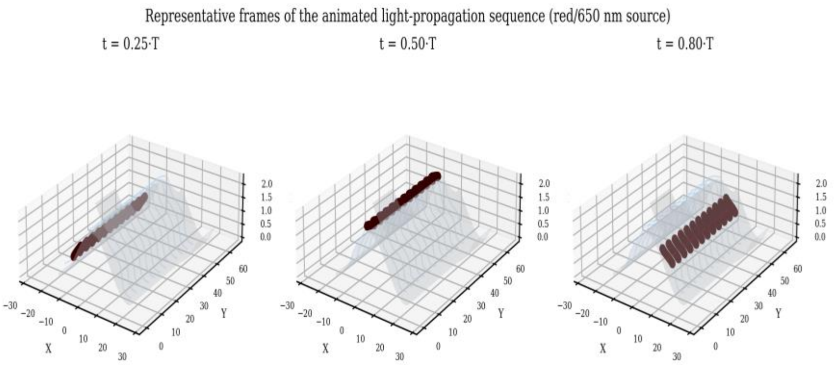

Figure 5. Representative frames from the animated sequence (red / 650 nm source).

Expanded Sensitivity Analysis

An expanded one-way sensitivity study varied splitter efficiency η, bulk attenuation α, bend prefactor β, path curvature κ, stretch amplitude ε, stretch-loss scale s and fibre length L over approximately ±20% about baseline (green-channel settings). Distal intensity at normalised length d = 1 was the response metric. Results are archived in Supplementary_data_2_sensitivity.csv.

Under the tested ranges, distal intensity was most sensitive to bulk attenuation α and to fibre length L (each producing up to about 55% change relative to baseline when scaled ±20%), moderately sensitive to splitter efficiency η (up to about 20%, as expected from direct proportionality) and to bend parameters β and κ (up to about 13%), and only weakly sensitive to stretch amplitude and stretch-loss scale (under 1% for ±20% changes at the baseline ε = 0.10). Refractive-index variation with n_clad fixed changes the critical angle θ_c from about 73.6° to 69.0° over n_core ∈ [1.47, 1.51] (Supplementary_data_3) but does not alter the intensity formula in the present model once guidance is assumed. These rankings reinforce that absolute brightness predictions remain order-of-magnitude guidance until α, β and η are measured for the intended components.

Practical Implications for Clothing Designers

Designers can compare source colours for distal brightness, flag serpentine turning points and sleeve–shoulder transitions as bend-loss hotspots, and form a first-order splitter power budget before committing to physical fibre and diodes. The framework is intended to reduce early prototype count and material waste, not to replace laboratory characterisation.

Limitations

This article is a computational proof-of-concept and pre-fabrication design framework. It is not a validated digital twin of a physical garment. Physical laboratory characterisation of polymer optical fibre, splitter hardware and garment prototypes lies outside the present scope.

Loss coefficients α, β and s, and splitter efficiency η, are illustrative. The garment surface does not resolve yarn- or weave-level interaction or side-emission texture. Wearer comfort, wash durability and long-term reliability are not assessed [10], [19], [20]. LED electrical, thermal and eye-safety checks are not included [17]. No physical attenuation or bend-loss measurements are reported. Full uncertainty quantification against laboratory data remains contingent on the measurements specified in Section 6.

RECOMMENDED EVALUATION PROTOCOL

Physical measurement is the highest-priority next step. Required parameters include refractive index, numerical aperture, attenuation (dB/m at 450/532/650 nm), splitter insertion loss, macro-bend loss, optical power, strain sensitivity, mechanical strength and wash durability. Even a small controlled pilot comparing measured and simulated attenuation at the three wavelengths on a few fibre lengths would substantially strengthen future versions of this work.

Pre-registered validation design: $n \geq 5$ physical fibre samples per source wavelength, each measured in triplicate with a calibrated optical power meter, reporting mean ± standard deviation. Agreement with the Beer–Lambert prediction will be quantified by R^2 and RMSE. The same design logic should be applied to bend-loss and strain-sensitivity checks.

CONCLUSION AND FUTURE WORK

This paper presented a MATLAB-based computational proof-of-concept and pre-fabrication design framework for a twelve-channel RGB optical-fibre smart T-shirt. It unifies parametric garment geometry, serpentine multi-channel routing, splitter power budgeting and multi-mechanism optical loss in an interactive visualisation environment. Results illustrate relative colour behaviour and design sensitivity under explicitly illustrative coefficients; they do not claim calibrated prediction of a physical product. The expanded sensitivity analysis identifies bulk attenuation and fibre length as the most influential parameters among those tested.

Future work will replace illustrative coefficients with measured values; execute at least a pilot physical comparison of attenuation at the three design wavelengths; extend the model toward weave-level fibre–fabric interaction; and deposit the MATLAB source code, parameter tables and simulation outputs in a public repository with a DOI so that other researchers can reproduce and extend the framework.

Declarations

Funding

This research received no external funding.

Conflicts of Interest

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

Data Availability

Upon acceptance, the MATLAB source code, simulation parameters, sensitivity datasets and exported animation will be deposited in a public repository (for example Zenodo or GitHub with a permanent DOI) to support reproducibility of this computational research. Until deposit is complete, materials are available from the corresponding author on reasonable request. Synthetic attenuation series in the supplementary files demonstrate the validation workflow only and are not physical experimental measurements.

Ethics Statement

This study did not involve human participants, animal subjects or personal data. Ethical approval was not required.

Author Contributions

Sourov Kumar Paul: Conceptualization, Methodology, Software, Writing – original draft. Joy Biswas: Formal analysis, Validation, Writing – review and editing. Badhon Saha: Investigation, Resources, Writing – review and editing. Md. Shahin Khandaker Nayem: Investigation, Writing – review and editing. Pranta Saha: Investigation, Writing – review and editing. Md. Mahmudul Hasan: Investigation, Writing – review and editing. All authors approved the final manuscript.

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