nature portfolio

Peer Review File

Wearable textile-based phototherapy platform with customized NIR OLEDs toward non-invasive hair loss treatment

Corresponding Author: Professor Kyung Cheol Choi

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The manuscript “Wearable textile based phototherapy with customized near infrared OLEDs for superior hair loss treatment” by Cho et al. presents an integrated phototherapeutic platform that couples wavelength-tuned, top-emitting NIR OLEDs with a textile substrate for non-invasive, ergonomic hair loss treatment. The authors engineered a microcavity OLED architecture to precisely match the NIR emission spectrum (700–800 nm) to the activation profile of human dermal papilla cells (hDPCs), the key cell type involved in follicular regeneration. The resulting devices exhibit mechanical robustness (tolerating 10,000 bending cycles), water resistance (over 90% radiance retention after 50 h submersion), and thermal safety (<30 °C skin-contact temperature under continuous use), all while preserving high optical output and directional emission.

From a technical perspective, the work is well-executed in some aspect. The use of Ag-based reflective electrodes, HTL/ETL thickness modulation for spectral tuning, and parylene-C encapsulation are appropriate choices for realizing narrowband top-emitting OLEDs. The optical tuning to the cytochrome c oxidase absorption window is biologically relevant and represents thoughtful device-biology integration.

However, the degree of novelty and scope of biological validation should have significant room for improvement, which makes us concerned that the current work does not match the level of Nature Communications.

Major comments:

Although we have some concerns above, I recognize the authors demonstrate commendable effort in showing a solid command of microsystem assembly. Additionally, the manuscript presents a promising attempt to address meaningful medical needs, the superior hair loss treatment. It is one promising and attractive research direction. Here are some detailed concerns on the current manuscript.

1.The scope of biological validation is limited to in vitro studies. While the scratch assay and β-galactosidase staining on hDPCs demonstrate promising cellular outcomes, no systematic in vivo validation is provided. This weakens the therapeutic relevance of the claims. The authors should consider adding systematic in vivo studies to assess light penetration, dose delivery, and its overall effectiveness.

2.The significance of this paper can be modified to state more clearly. It can be improved while benchmarking against clinical or FDA-cleared phototherapy systems. Without sufficient comparison to red-light helmets or laser-based PBM devices, it is unclear whether the proposed OLED system offers a distinctive, meaningful clinical advantage. The authors could consider adding irradiance, power density, and angular emission data to support their claims of improved therapeutic delivery.

3.The innovation presented in this work appears to lie primarily in the thoughtful integration of several established device technologies into a wearable phototherapy platform. Microcavity-tuned OLEDs, reflective Ag electrodes, textile substrates, and parylene encapsulation are all well-documented in prior OLED and wearable electronics literature. While the

combination here is executed effectively and tailored to a biologically relevant spectral window, the manuscript would benefit from a clearer articulation of how this integration offers concrete advances over previously reported wearable PBM systems. For instance, prior studies on cage-type OLEDs and micro-LED arrays have also addressed flexibility and form factor, albeit with different approaches and trade-offs.

Reviewer #2

(Remarks to the Author)
This paper presents the development and validation of a novel, fully wearable phototherapy system that integrates microcavity-tuned, top-emitting near-infrared (NIR) OLEDs into textiles, precisely engineered to match the activation spectrum of human dermal papilla cells (hDPCs) for non-invasive, effective hair regeneration via photobiomodulation (PBM), while addressing the limitations of conventional pharmacological and light-based therapies for alopecia. Overall, this is an interesting work and can be recommended for publication in Nature Communications after major revision. The following are some comments that might be helpful for further improvement of their manuscript to publish in future publications.

1. The paper claims tuning to match the action spectrum of hDPCs via CCO activation. However, CCO's absorption range is broad and varies across mitochondrial states. What is the justification for targeting 730 nm and 800 nm specifically, and how do these correspond to CCO isoforms or ROS generation thresholds in vivo?
2. All validation was performed using 2D hDPC monolayers. However, in vivo hair follicles reside within a 3D dermal environment and are exposed to vasculature, hormones, and other cell types. How do you account for the translational gap between 2D in vitro data and actual follicular behavior?
3. The authors claim the cavity NIR OLED is superior, yet the non-cavity NIR showed greater hDPC migration after 16 hours. How do they reconcile this observation with their main claim of improved performance via cavity tuning? Could this be related to angular distribution or unintended dose differences?
4. With such spatial and angular variations in emission, how do you control for accurate irradiance delivery over curved, irregular scalp surfaces? Are there active or passive dosimetry mechanisms built into the textile?
5. The study attributes effects to CCO activation and ROS signaling, but presents no direct biochemical validation (e.g., ROS quantification, antioxidant gene expression, or ATP production levels). Why was no such mechanistic validation performed?
6. The pigskin model is useful, but did the authors perform Monte Carlo simulations or tissue-mimicking phantoms to more precisely model photon distribution to the follicle base (~3 mm)? 12% transmission is relative—how much actual photon energy reaches target biological chromophores?
7. Has the team quantified how the refractive index mismatch between parylene-C and human skin affects photon loss via internal reflection or scattering? Could this be mitigated with intermediate index-matching layers?
8. Your microcavity devices show ~40 nm FWHM. Some studies suggest broader bandwidths (~100 nm) can stimulate a wider range of cellular photoreceptors. Could overly narrow spectral targeting reduce holistic tissue activation?
9. While HTL-tuned microcavity devices show higher EQE than ETL-tuned ones, did you quantify trade-offs in carrier balance, recombination zone position, or angular intensity losses at oblique angles? How does the angular spectral stability compare under real-world usage conditions?
10. The manuscript claims 'markedly superior efficacy' of the textile-integrated NIR OLED system compared to conventional phototherapy methods. However, there is no quantitative benchmarking against existing commercial or clinically validated devices (e.g., LLLT helmets like iRestore, HairMax, or LG Pra.L Medi Hair). Can the authors provide a controlled, side-by-side comparison of their device's therapeutic outcomes — such as hDPC migration rates, senescence reduction, and transdermal photon flux — relative to these established devices under matched irradiance and exposure conditions? Without such benchmarking, how can superiority over current clinical standards be substantiated?"
11. OLEDs are known to suffer from current spreading issues and voltage gradients on large substrates. How do you ensure homogeneity of brightness across a large, curved textile interface?
12. How consistent are key performance metrics such as luminance, EQE, FWHM, and turn-on voltage across batches? What is the coefficient of variation in performance across 10+ fabricated devices?
13. Given that EQE roll-off is a critical issue in NIR OLEDs due to triplet-triplet annihilation and thermal quenching, what is the trade-off between brightness and stability? Have you characterized thermal degradation and emission roll-off in that regime?
14. In this work, the merit and demerit of the textile-integrated near-infrared OLED system should be discussed when applied to biocompatible platforms for non-invasive wearable phototherapy.

Reviewer #3

(Remarks to the Author)
The authors did solid OLED engineering work, showing how the proposed device optimization leads to better biological response compared to others (not optimized or similar to commercially available products). The methodology is sound, and the work could be of significance in the field of wearable electronics if adjustments to the manuscripts are properly made.

The major point I have is about wearability and usability of the presented device in real life scenarios.
The general idea of this work presupposes the existence of a supporting circuitry that ideally fits into the hat, and is removable when washing is necessary (Of course, more creative solutions could be implemented to realize portability, this was just an example).
In this regard, I failed to find information about the driving scheme used to realize the videos proposed as demonstrations. For this reason, at the present time, there is the need to add data about this aspect to fully comply with the message of portability proposed in the manuscript, and also to show that this device is indeed compatible with the notion of wearable

electronic platforms. In other words, the OLED per se is wearable, but the phototherapy (quoting the title that the authors chose) probably still relies on benchtop power supplies. Therefore, I suggest that the authors come up with a circuitry that allows the OLED to be driven in a truly portable fashion, demonstrating that with the application requirements, the power supply (maybe a battery) can be sufficient to drive the OLED for a substantial amount of time (or equivalently, enough therapeutic sessions). This should be documented in the method section and shown in a Figure.

I have some minor comments referring to the different sections of the manuscripts.
ROW 102: “Additionally, most NIR OLEDs have been designed a bottom-emitting architecture” probably contains an error.
ROWS 115-116: Typically, bottom emitting OLEDs provide different advantages over top-emitting ones. While it is clear that bottom emitting devices based on ITO are susceptible to mechanical damage under certain stress, the author here exclude the whole category of bottom-emitting OLEDs without addressing the general motivation. Could they elaborate more on this design choice?
ROW 128: Why are the authors using this specific tensile strain (2.1%)? What are the ranges of expected strains during use and during washing of the “hat”? It is suspected that this object will face grater deformations for the intended wearable application. What would be the number of bending tests that the OLED would tolerate for a strain in the range conform to the application needs?
ROW 183: I think the authors should reference figures 3 and 5 here.
ROWS 246—248: It is useful for the reader to directly access the information about the ETL and HTL thickness from this line. Could the authors explicitly state the thicknesses in the non-optimized VS. optimized case and provide an explanation for their claim on the better carrier transport in the optimized configuration?
ROW 307: What are the requirements in terms of optical power density (or equivalently energy density) that are required to exhert relevant beneficial effects with this type of therapy? This information is difficult to retrieve without accessing to reference 7. I think it would be of service to explicitly mention this in the text. It is also important to state at what voltages and currents the OLEDs presented in this work reach this range.
ROW 320: See the comment related to the choice of a 2.1% strain.
ROW 341: I think the content of ROWS 355-361 should be moved here for better readability.
ROW 495: It would be appropriate to show a plot with the superposition of hDPC activation spectrum (or peak if not available) and the different OLEDs EL spectra. Most probably the authors can add the hDPC missing information directly into figure 2E.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have substantially revised the manuscript “Wearable textile-based phototherapy with customized near-infrared OLEDs for superior hair loss treatment” in response to the first-round reviews. In particular, they added (1) pilot in vivo experiments using a mouse model together with ex vivo skin-penetration measurements, (2) quantitative analysis of power density and on-cell irradiance supported by Monte Carlo simulations in a layered skin model, and (3) a clearer positioning of their textile NIR OLED platform relative to commercial PBM devices and previously reported cage-OLED / micro-LED systems.

I thank the authors for their detailed and constructive revision. The additions to the manuscript and response letter clearly show substantial effort. The new data and analysis improve the rigour of the optical characterization and strengthen the positioning of the textile-integrated NIR OLED platform.

My major concerns about optical dose characterization and benchmarking (previous Comments 2 and 3) are now largely addressed. The remaining weakness is that in vivo validation of therapeutic efficacy is still preliminary: the new data mainly document light delivery through murine skin and ongoing animal studies, but do not yet demonstrate hair-growth outcomes or dose–response relationships. The authors have, however, clarified these limitations and softened their claims.

Given the device-centric nature of the work and the strengthened quantitative analysis of light delivery, I believe the manuscript is now much closer to the bar of Nature Communications. I would be comfortable with publication after minor revision, mainly to ensure that the limited status of the in vivo data is clearly conveyed in the main text.

Major comments:

1. Regarding previous comments on the scope of biological validation / in vivo relevance.

These additions partially address my original concern. In particular:

(1) The skin-penetration measurements are useful and directly relevant to the question of whether sufficient NIR power can reach the follicular region in a realistic setting.

(2) The explicit acknowledgment that full in vivo hair-growth validation is ongoing and non-trivial makes the biological scope of the current work more honest and transparent.

However, the in vivo component remains exploratory rather than systematic. The material presented in Fig. R1 mainly documents the experimental setup rather than quantitative biological outcomes (e.g., hair-density maps, histology, or longitudinal regrowth curves). I understand that performing a comprehensive preclinical efficacy study may be beyond the scope of this device-focused paper; in that case, the main text should clearly avoid overstating therapeutic claims.

Therefore, in the revised manuscript, please ensure that statements about “superior hair-loss treatment” or “therapeutic efficacy” are toned down and framed as potential or anticipated benefits supported by cellular assays and realistic light-delivery analysis, rather than as fully demonstrated in vivo outcomes.

It would also be helpful to summarize the key quantitative numbers from the skin-penetration experiment (relative radiance with shaved vs. depilated skin) in the main text or a main-figure panel, not just in the response.

2. Regarding benchmarking vs FDA-cleared clinical systems.

The revisions substantially strengthen the manuscript. The combination of measured irradiance, modelled dose in tissue, and angular emission data now provides a quantitative and mechanistic basis for discussing light delivery, rather than relying on qualitative statements alone. The benchmarking against commercial devices is necessarily limited by the sparse publicly available specifications, but the discussion is reasonable and helps to contextualize the work.

Moreover, I suggest ensuring that typical ranges of fluence and irradiance used in clinical PBM protocols are cited and that your operating regime is clearly positioned within those ranges. This will help readers outside the PBM community interpret the numbers.

Consider summarizing the key benchmarking parameters (e.g., wavelength, approximate irradiance at the scalp, form factor) in a compact comparison table in the main text, even if the underlying details remain in the Supplementary materials.

Minor comments:

1. When discussing the in vivo mouse work, I suggest avoiding explanations that could be interpreted as complete therapeutic validation; instead, emphasize that these are pilot studies demonstrating the feasibility of light delivery and setup for future efficacy experiments.

2. I suggest some careful edits to remove any remaining instances of over-strong claims, such as “superior hair loss treatment” in contexts where in vivo hair regrowth is not yet shown, which would improve the overall balance of the manuscript.

Reviewer #2

(Remarks to the Author)
The authors well-replied and address the concerned sections. Therefore, I suggested that the current revised manuscript can be accepted by Nature Communications.

Reviewer #3

(Remarks to the Author)
Amazing work.

Manuscript Number: NCOMMS-25-35152B
Title: "Wearable textile-based phototherapy with customized near-infrared OLEDs for superior hair loss treatment"
Correspondence Author: Eun Hae Cho, Jingi An, Yun Chi and Kyung Cheol Choi.

Responses to the reviewer's comments

November 6, 2025

Dear Reviewers,

Let us open by thanking the reviewers for their insightful comments. The reviewers gave us clear guidance and some positive critiques. Following the reviewers' suggestion, we spent more time reading and came to the revision process better prepared. We enjoyed the process and think that the reviewers' comments have tremendously improved the revised draft. The reviewers should now clearly see the difference they made to the revised manuscript. In the following lines, we detail the responses and changes that were made in line with the reviewers' comments. The reviewers' comments are highlighted in bold type. In the manuscript, the revisions addressing the reviewers' comments are highlighted in red, and the voluntary modifications are highlighted in blue.

Responses to the reviewer 1's comments

Reviewer #1: The manuscript "Wearable textile-based phototherapy with customized near infrared OLEDs for superior hair loss treatment" by Cho et al. presents an integrated phototherapeutic platform that couples wavelength-tuned, top-emitting NIR OLEDs with a textile substrate for non-invasive, ergonomic hair loss treatment. The authors engineered a microcavity OLED architecture to precisely match the NIR emission spectrum (700–800 nm) to the activation profile of human dermal papilla cells (hDPCs), the key cell type involved in follicular regeneration. The resulting devices exhibit mechanical robustness (tolerating 10,000 bending cycles), water resistance (over 90% radiance retention after 50 h submersion), and thermal safety (<30 °C skin-contact temperature under continuous use), all while preserving high optical output and directional emission. From a technical perspective, the work is well-executed in some aspect. The use of Ag-based reflective electrodes, HTL/ETL thickness modulation for spectral tuning, and parylene-C encapsulation are appropriate choices for realizing narrowband top-emitting OLEDs. The optical tuning to the cytochrome c oxidase absorption window is biologically relevant and represents thoughtful device-biology integration. However, the degree of novelty and scope of biological validation should have significant room for improvement, which makes us concerned that the current work does not match the level of Nature Communications.

RESPONSE

We thank the reviewer for the insightful comments and for their interest in our research. The following are our responses to the individual comments.

Reviewer's comment 1) The scope of biological validation is limited to in vitro studies. While the scratch assay and β-galactosidase staining on hDPCs demonstrate promising cellular outcomes, no systematic in vivo validation is provided. This weakens the therapeutic relevance of the claims. The authors should consider adding systematic in vivo studies to assess light penetration, dose delivery, and its overall effectiveness.

RESPONSE

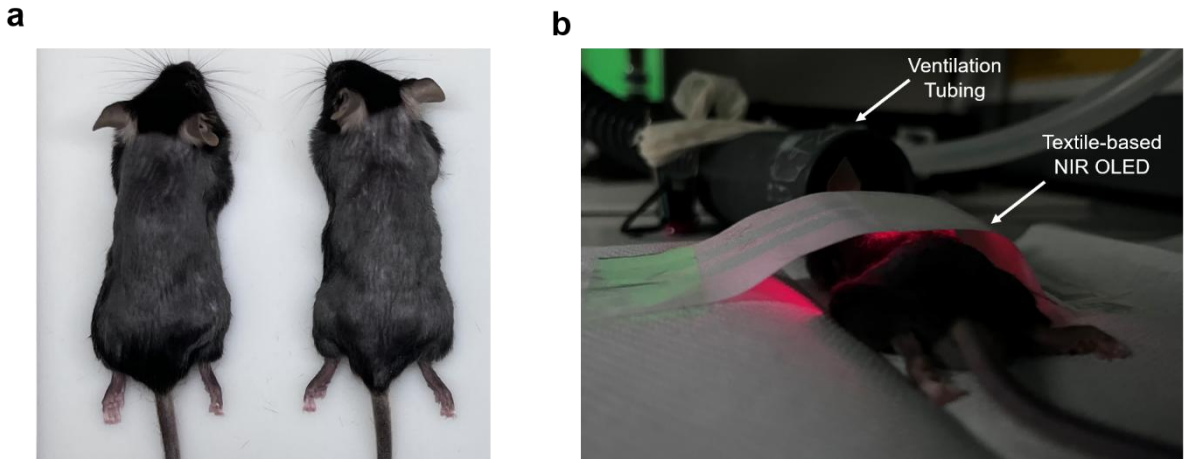
We appreciate the reviewer's comment regarding the limited scope of biological validation. In fact, subsequent *in vivo* study is underway. We provide a brief overview of our ongoing *in vivo* work using textile-based OLED devices.

- **Follow up research about *in vivo* test using the textile-based OLEDs**

As part of an ongoing, follow-up study to evaluate PBM in vivo, the textile-based NIR OLED was applied to C57BL/6 mouse model to validate PBM effect for hair-loss treatment. A dorsal skin was trimmed to ~1 mm using an electric razor, with careful control to avoid wounding, as skin injury itself can artificially induce hair regrowth **(FigR.1a)**. Light irradiation

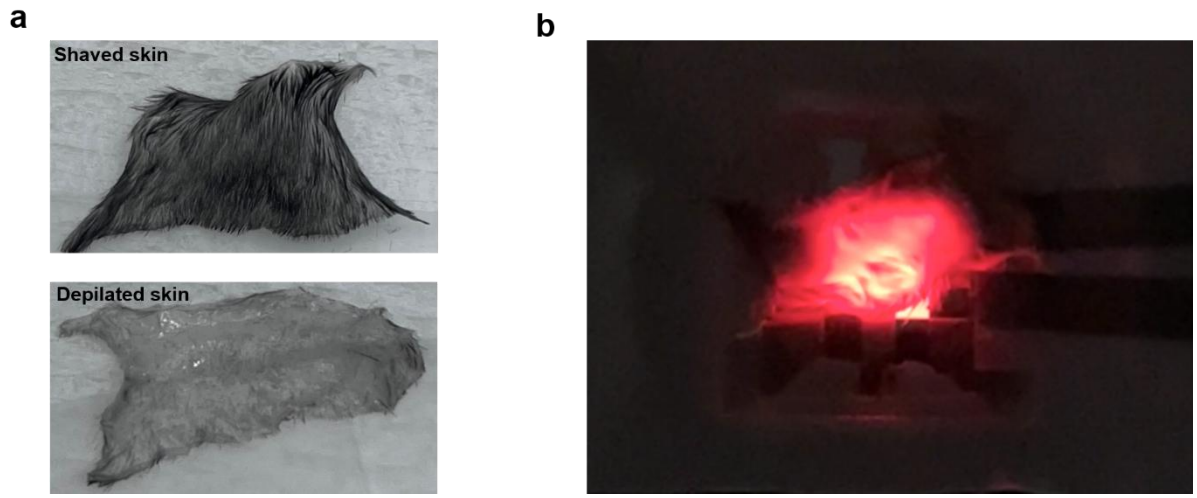
was performed under respiratory anesthesia at 730 nm (± 5 nm), 3 mW cm^{-2}, for 20 minutes per day, which were the same conditions as those used for the *in vitro* test in this study. The same dorsal region was targeted at a fixed time each day **(FigR.1b)**.

Based on the experiments described above, we are currently setting the experimental conditions by optimizing both the animal model and the OLED irradiation parameters.



FigR.1 | *In vivo* validation of phototherapy. a, Mouse after dorsal hair removal (shaved). **b,** Photograph of irradiation during wearable phototherapy with the textile-based NIR OLED.

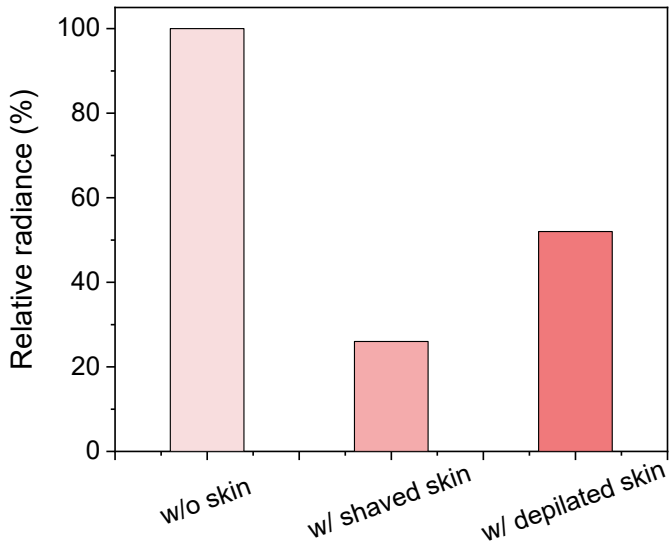
■ **Light penetration after penetration of mice skin**



FigR.1 | Light transmission of the textile-based OLED. a, Photograph of shaved and depilated mouse skin prepared for *in vivo* phototherapy. **b,** Emission image of the textile-based OLED placed beneath the mouse skin.

This experiment was designed to examine whether residual fine hair attenuated light energy and to verify whether OLED irradiation delivered sufficient optical power to the hair follicles. As shown in **FigR.2a**, both shaved skin and fully depilated skin were excised from mice to prepare skin tissue samples. These tissues were placed directly on the OLED emission surface, and the transmitted light intensity was measured **(FigR.2b).** Even though with residual hair, approximately 26% of the emitted light penetrated through the skin, while fully depilated skin transmitted about 52% (**FigR.3**).

Although some attenuation was caused by hair, these values indicate that a considerable portion of the OLED emission was still transmitted, and the resulting irradiance was well above the effective dose established in our *in vitro* assays (please refer to **our response to Reviewer 2, Comment 3**).



FigR.3 | Light intensity measured after transmission through each mouse skin condition.

■ Conclusion

The NIR OLED constitute a non-invasive light-delivery modality capable of activating DP cells within the skin. However, *in vivo* validation of hair growth, unlike *in vitro* assays, cannot rely solely on cellular activation, as outcomes are strongly influenced by signaling dynamics governed by the murine hair-cycle stage. Accordingly, optimization of the animal model and PBM irradiation parameters (irradiance and treated period) is in progress for the *in vivo* experiments.

Reviewer's comment 2) The significance of this paper can be modified to state more clearly. It can be improved while benchmarking against clinical or FDA-cleared phototherapy systems. Without sufficient comparison to red-light helmets or laser-based PBM devices, it is unclear whether the proposed OLED system offers a distinctive, meaningful clinical advantage. The authors could consider adding irradiance, power density, and angular emission data to support their claims of improved therapeutic delivery.

RESPONSE

We appreciate the reviewer's suggestion to benchmark our OLED system against clinical or FDA-cleared phototherapy systems to better highlight its distinctive advantages. To more clearly delineate the advantages of our device relative to existing systems, additional datasets and simulations were included to revised manuscript.

1. **Quantifying NIR OLED power density and on-cell irradiance**

To validate clearly our NIR OLEDs light effect to cell medium, we design our in-vitro set up for monte carlo simulation and simulated it to define a light effect. In vitro irradiation was executed at a source power density of 3 $mW \cdot cm^{-2}$ for 20 minutes, selected to remain within the commonly reported PBM therapeutic window while ensuring safe exposure for cultured dermal papilla cells. Under our culture geometry, the on-cell irradiance was estimated at approximately 2% of the source value, yielding ~ 0.06 $mW \cdot cm^{-2}$. This corresponds to a fluence of 0.72 $J \cdot cm^{-2}$. Despite the low dose, the NIR OLED condition yielded a reduction in cellular senescence markers relative to the red-light control in the same assay by about 90% under otherwise matched exposure. This difference was attributed to spectral matching of the customized NIR OLED to the dermal papilla cell action spectrum rather than to an increase in total dose. Details are provided in the Response **to Reviewer 2, Comment 3**.

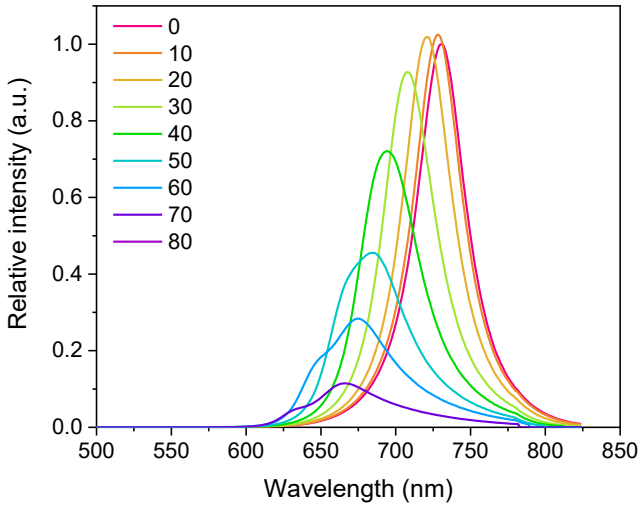
2. **Simulation for real skin model relevant skin model**

To translate source emission into depth-resolved dose under anatomically relevant conditions, three-dimensional Monte Carlo simulations were performed using a layered human-skin model. The simulations quantified post-penetration irradiance customized NIR (this study) OLEDs. The results indicated sufficient delivery of optical energy to dermal depths of approximately 3–5 mm in the NIR range, supporting the relevance of our wearable system, which could be close to scalp, emission for effective PBM. Details are provided in the Response to **Reviewer 2, Comment 6.**

3. Angular profile of NIR OLEDs

Typically, OLED emission is not confined to the forward direction; rather, its intrinsic angular distribution illuminates a broad tissue area, increasing the spatial coverage of optical stimulation. However, our NIR OLEDs exhibit angle-dependent spectral characteristics due to their microcavity effect **(Supplementary Fig. 13,** the figure is added for revised manuscript**).** On curved scalp geometries, such angular dispersion can introduce modest spectral shifts that alter the wavelength composition reaching the tissue. The angle-dependent blueshift of cavity OLEDs is a potential limitation for PBM applications targeting a band near 730 nm for hair-loss treatment.

Nevertheless, this limitation could be mitigated by incorporating scattering outcoupling layers, which stabilize the spectral peak across viewing angles and help maintain the designed NIR emission near 730 nm. We recognize this potential weakness but note that the inherent spectral shift of cavity OLEDs can be effectively alleviated using scattering layers or additional surface engineering **(**related with Response to **Reviewer 2, Comment 4).**



Supplementary Fig. 13| Emission spectra of cavity NIR OLEDs as a function of viewing angle.

Modifications to the revised manuscript in lines 427–430 of the Result section for providing the angular profile data.

In contrast, the cavity structure enhanced forward emission, achieving an angular distribution closer to a Lambertian profile. A blue shift of the EL spectrum with increasing viewing angle was observed in cavity NIR OLEDs, attributable to microcavity resonance that shifts the cavity mode toward shorter wavelengths with increased viewing angles **(Supplementary Fig. 13).**

4. Comparison with commercial phototherapy devices

Publicly available information on commercial devices (e.g., red-light helmets and laser-based PBM systems) rarely includes beam width, angular distribution, or wavelength-resolved irradiance at the tissue interface, which limits direct benchmarking. However, as elaborated in our responses to **Reviewer 2 (Comments 10 and 14),** compared with commercially available devices and previously reported platforms, our textile-based NIR OLEDs systematically leverages both the PBM advantages and the platform-level benefits for hair-loss treatment.

Furthermore, beyond validating optical delivery and demonstrating PBM efficacy, the principal qualitative advantage of the textile-based system is its compatibility with a familiar daily platform—a hat. Low-level laser devices are commonly implemented as helmet-type or otherwise bulky systems that constrain where and how they can be used. By contrast, the approach proposed here can be applied to conventional caps and integrated into the hat architecture. In addition, to demonstrate portability in a wearable textile-based phototherapy device, we fabricated a prototype composed entirely of flexible components—a flexible battery, an FPCB with an on/off switch and drive capability, and OLEDs—as shown in our Response to **Reviewer 3, Comment 1 (Supplementary Videos 4, 5).**

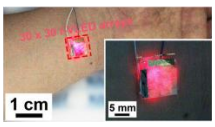
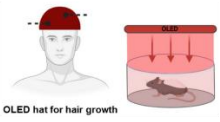
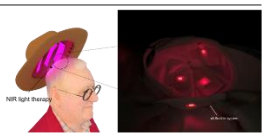
<u>Reviewer's comment 3)</u> The innovation presented in this work appears to lie primarily in the thoughtful integration of several established device technologies into a wearable phototherapy platform. Microcavity-tuned OLEDs, reflective Ag electrodes, textile substrates, and parylene encapsulation are all well-documented in prior OLED and wearable electronics literature. While the combination here is executed effectively and tailored to a biologically relevant spectral window, the manuscript would benefit from a clearer articulation of how this integration offers concrete advances over previously reported wearable PBM systems. For instance, prior studies on cage-type OLEDs and micro-LED arrays have also addressed flexibility and form factor, albeit with different approaches and trade-offs.

<u>RESPONSE</u>

We appreciate the reviewer's comment and agree that the manuscript will benefit from a clearer articulation of how the proposed platform offers concrete advances over previously reported wearable PBM systems.

Prior studies on micro-LED arrays and cage-type OLEDs have indeed addressed flexibility and form factor, but they remain limited by certain trade-offs. Micro-LED arrays have been demonstrated on flexible platforms, but their fabrication process is complex, and the small light sources make them unsuitable for large-area uniform irradiation.[1] Cage-type OLEDs have primarily been used to validate the therapeutic effects of red OLEDs on alopecia, which is valuable for demonstrating efficacy.[2] However, they offer limited significance in terms of new platform development, as the rigid platform restricts comfort and conformability, making them unsuitable for wearable devices (**TableR.1**).

Characteristics of phototherapy devices reported in previous studies

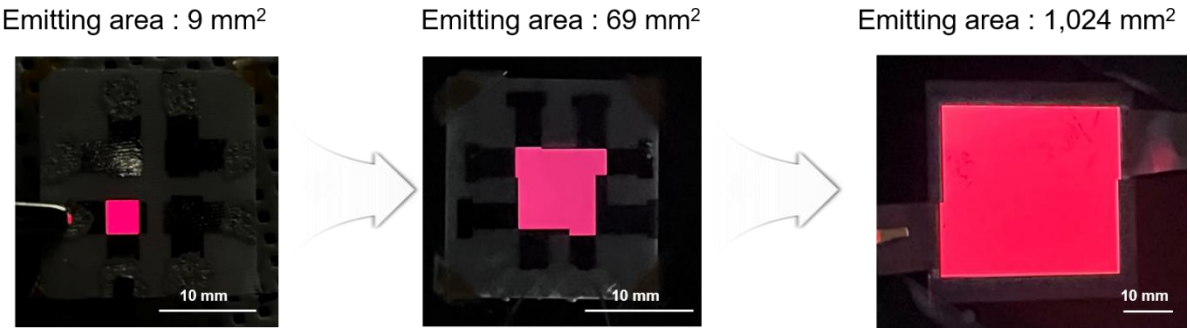
	Patch-type attachable μ-LED[1]	**Red** OLED **cage**[2]	**Textile**-based **NIR** OLED[This study]
Device			
Light source	μ-LED	OLED	OLED
Substrate	Polymer	Glass	Textile
Platform	Patch	Helmet	Hat
Flexibility	Flexible	Rigid	Flexible
Wavelength	Red (650 nm)	Red (640 nm)	NIR (730 nm)
Emission area of pixel	0.09 mm^2	7500 mm^2	70 mm^2

TableR.1 | Comparison of phototherapy devices reported in previous studies.

In contrast, our textile-based NIR OLED offers several distinctive advantages for PBM applications, specifically across three key aspects: the light source, the wavelength, and the platform.

1. Advantages of OLEDs

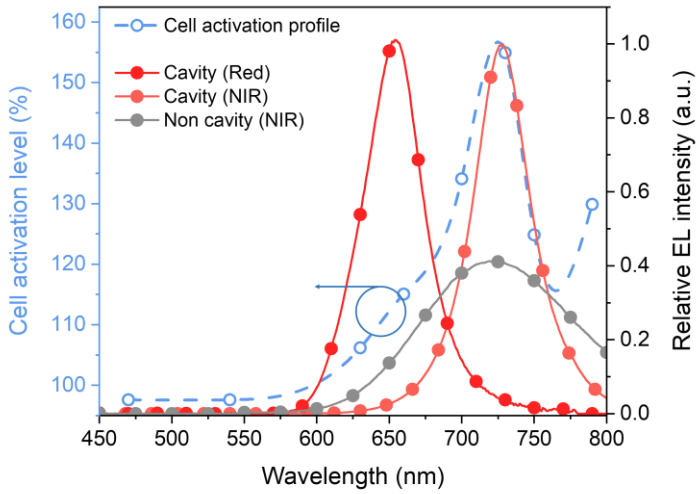
Compared with LEDs and lasers, OLEDs offer superior irradiance uniformity and design scalability. Because OLEDs are fabricated by mask-based vacuum deposition of organic layers, the emission area and shape can be freely patterned **(FigR.4)**. This allows fabrication of customized devices tailored to the geometry of alopecic scalp regions.



FigR.4 | Textile-based NIR OLEDs with each scale.

2. Advantages of NIR light (especially around 730 nm)

NIR light is well recognized for its ability to penetrate deeply into skin without significant energy loss. More importantly, PBM relies on wavelength-specific activation of cellular processes. From the perspective of alopecia treatment, NIR light, and specifically 730 nm, has been shown to outperform the red spectral range. Our previous work demonstrated that 730 nm light stimulates dermal papilla cell proliferation.[3] We further show that it effectively suppresses cellular senescence, thereby offering therapeutic advantages over conventional red-light PBM approaches in this study.



FigR.5 | Overlap between the cellular activation spectrum and the EL spectrum of each OLEDs.

3. Advantages of textile platform

Integration into a textile substrate enables use in hat-type devices, in contrast to adhesive patch systems. This form factor allows safe coverage over residual hair without direct adhesion to skin, enhancing both safety and user comfort. The device is lightweight, flexible, and can conform closely to the scalp. While textile-based phototherapy devices have been minimally explored (with few exceptions such as neonatal jaundice or PPG monitoring),[4,5] PBM applications have not yet been reported. Our work therefore introduces a new concept of textile-integrated OLEDs for phototherapy, expanding the scope of wearable biomedical applications.

Overall, these advances—uniform and customizable OLED emission, the biological advantages of NIR light at 730 nm, and a textile-based platform optimized for practical, comfortable wear—distinguish our system from previously reported wearable PBM devices. The above content has been added to the revised manuscript.

References

[R1] Lee, H.E., Lee, S.H., Jeong, M., Shin, J.H., Ahn, Y., Kim, D., Oh, S.H., Yun, S.H. & Lee, K.J. *ACS Nano*, 12, 9587-9595 (2018).

[R2] Sun, S.-Q., Shen, J.-J., Wang, Y.-F., Jiang, Y.-T., Chen, L.-F., Xin, H., Wang, J.-N., Shi, X.-B., Zhu, X.-Z., Sun, Q., Liao, L.-S., Chen, Q., Fung, M.-K. & Lee, S.-T. *Nano Research*,

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[R3] Cho, E. H., Choi, H.-R., Park, Y., Jeong, S. Y., Song, Y. J., Hwang, Y. H., Lee, J., Chi, Y., Wang, S.-F., Jeon, Y., Huh, C.-H. & Choi, K. C. *ACS Appl. Mater. Interfaces* 15, 57415–57426 (2023).

[R4] Choi, S., Jeon, Y., Kwon, J. H., Ihm, C., Kim, S. Y. & Choi, K. C. *Adv. Sci.* 9, 2204622 (2022).

[R5] Lee, H. S., Kong, S. U., Kwon, S., Cho, H.-E., Noh, B., Hwang, Y. H., Choi, S., Kim, D., Han, J. H., Lee, T.-W., Jeon, Y. & Choi, K. C. *ACS Nano* 18, 20363–20379 (2024).

Modifications to the revised manuscript in lines 64–87 of the Introduction section

Micro-LED patches offer a more flexible form factor than rigid helmet or home-use phototherapy systems and can improve conformity to skin. However, limitations arise from the patch architecture and the micro-scale emitting area of individual sources. Because attachment typically relies on skin adhesives, patches can inadvertently induce hair traction during application and removal, which is a non-trivial concern for patients with weakened hair follicle anchorage.[10] Moreover, the pixelated point-source nature of micro-LEDs complicates scaling to large treatment areas and tends to produce non-uniform irradiance with local hot spots, thereby limiting dose homogeneity across the scalp. Motivated by these constraints, OLED-based phototherapy device has been suggested. Unlike conventional light sources for phototherapy device, such as LEDs and lasers, OLEDs offer a combination of ultra-thin, flexible form factors and uniform light emission. A OLED-based platform provides large, homogeneous emission and have been reported to induce PBM relevant to hair-loss treatment.[11] However, barriers to day-to-day wearability persist. The platform has been designed for helmet-type configurations, paralleling commercial systems such as iRestore and LG Pra.L Medi Hair, and therefore do not fully exploit core OLED attributes—low mass, thin profiles, and mechanical flexibility.

Furthermore, the light irradiation should be capable of inducing hair growth. The PBM effect depends on the target cell type and wavelength band. Recent studies indicate that human dermal papilla cells (hDPCs), which play a crucial role in hair regeneration,[12] exhibit enhanced proliferation after exposure to near-infrared (NIR) irradiation compared with red light at the same dose, providing the importance of selecting an optimal wavelength for effective treatment.[13,14]

Responses to the reviewer 2's comments

Reviewer #2: This paper presents the development and validation of a novel, fully wearable phototherapy system that integrates microcavity-tuned, top-emitting near-infrared (NIR) OLEDs into textiles, precisely engineered to match the activation spectrum of human dermal papilla cells (hDPCs) for non-invasive, effective hair regeneration via photobiomodulation (PBM), while addressing the limitations of conventional pharmacological and light-based therapies for alopecia. Overall, this is an interesting work and can be recommended for publication in Nature Communications after major revision. The following are some comments that might be helpful for further improvement of their manuscript to publish in future publications.

RESPONSE

We are grateful for the reviewer's careful assessment and insightful suggestions. These comments provided a valuable opportunity to enhance the manuscript. Our responses to each comment follow.

Reviewer's comment 1) The paper claims tuning to match the action spectrum of hDPCs via CCO activation. However, CCO's absorption range is broad and varies across mitochondrial states. What is the justification for targeting 730 nm and 800 nm specifically, and how do these correspond to CCO isoforms or ROS generation thresholds in vivo?

RESPONSE

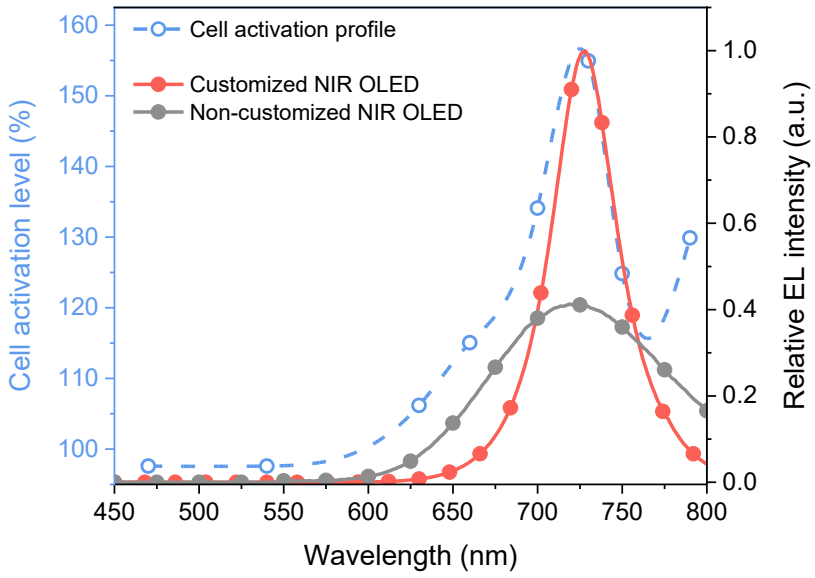
We appreciate the reviewer's insightful comment regarding the broad absorption spectrum of cytochrome c oxidase (CCO). Indeed, CCO exhibits multiple absorption peaks, and the overall absorption profile is influenced by the chromophores present in mitochondria, which vary between different cell types. As a result, the wavelength-dependent activation profile of cells differs according to cell type. Recognizing this, we tuned the emission of our textile-based OLEDs based on experimental data from **Cho, Eun Hae, et al. ACS Applied Materials & Interfaces 15, 57415–57426 (2023),** which had previously been obtained by our group.

- **Justification for selecting 730 nm**

To make clear the reason for designing our NIR OLED at 730 nm, we have now included in **Fig.5d**. This figure presents a direct comparison between the wavelength-dependent activation profile of dermal papilla cells, as verified in our earlier studies, and the emission spectra of our customized and non-customized OLEDs. Both OLEDs were normalized to the same radiance for this comparison.

To demonstrate spectral tunability of the NIR OLED platform and to enable wavelength-dependent penetration comparisons, an additional device with a main emission peak at approximately 800 nm was fabricated by adjusting the optical cavity. The 800 nm device was fabricated to demonstrate spectral tunability and to support penetration analysis, but it was not used in the in vitro assays focused on hDPC activation near 730–740 nm.

The *in vitro* experiments targeted dermal papilla cell activation, whose action spectrum peaks at 730–740 nm; therefore, under equivalent dose conditions, the 730–740 nm device provides the most appropriate stimulus. In view of this spectrum, the 800 nm device is less aligned with the activation peak than the 730–740 nm device. You can see the advantage of the customized NIR OLED in response to your **Comment 8**.

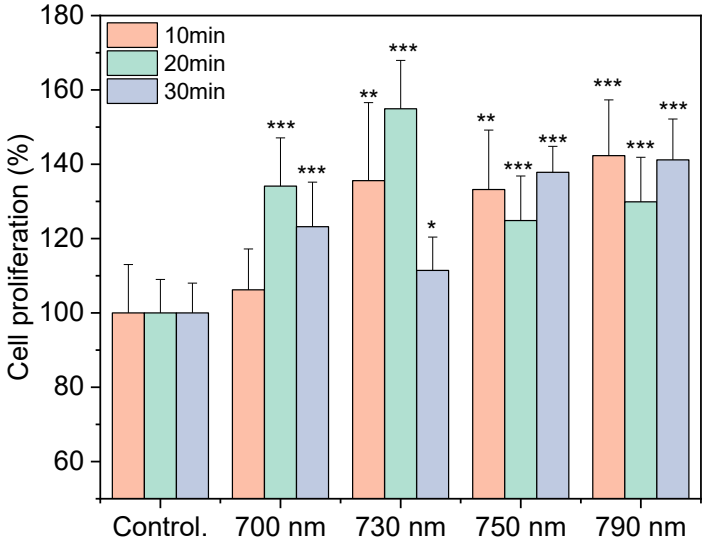


Modified Fig. 5d | Overlap between the human dermal papilla cell action spectrum for proliferation[13] and the EL spectra of the cavity NIR OLED and non-cavity NIR OLED under same radiance

■ **Correspondence to CCO Isoforms and ROS Generation Thresholds**

In terms of ROS thresholds, PBM enhances mitochondrial output through the transient production of ROS as signaling molecules. This response follows a hormetic paradigm: low-to-moderate increases in ROS act as beneficial messengers, whereas excessive ROS can be detrimental. The key is that PBM is delivered within safe irradiance and fluence ranges, ensuring that ROS remain in a range that upregulates antioxidant defenses, growth factors, and

proliferative signals without exceeding cytotoxic thresholds[1]



FigR.6 | hDPC proliferation versus illumination wavelength and exposure time (10–30 min), normalized to the non-irradiated control.[2]

In our previous research,[2] we evaluated dermal papilla cell proliferation as a function of wavelength and exposure time. Under illumination at 730–740 nm, a 20 min exposure produced a greater increase in proliferation than both 10 min and 30 min exposures, demonstrating a biphasic dose–response (**FigR.6**). These findings were used to optimize the OLED emission wavelength and dose conditions.

In the present study, using the optimized regimen (730–740 nm for 20 min), we performed in vitro assays of cell migration and cellular senescence. In the senescence assay, the customized NIR OLED provided the lowest levels of senescence-associated readouts among the tested conditions.

Our in vitro assays were performed under dose-matched conditions, with the irradiance delivered to the cell medium standardized across OLED groups (see our response to your **Comment 3** for details). The experiments quantified wavelength-dependent changes in cellular activation and highlighted the importance of wavelength tuning.

Consistent with the reviewer's point, tissue penetration in noninvasive phototherapy varies with wavelength. Therefore, *in vivo* comparisons conducted under identical fluence constraints would require wavelength-specific adjustment of OLED power density to achieve matched

tissue-delivered dose. However, PBM is influenced by irradiation wavelength. Thus, the 730–740 nm device, which is aligned with the hDPC activation peak, could lead to greater cellular activation than the 800 nm device under dose-matched conditions.

References

[R1] Chen, A. C.-H., Huang, Y.-Y., Sharma, S. K. & Hamblin, M. R. Photomed. Laser Surg. 29, 383–389 (2011).

[R2] Cho, E. H., Choi, H.-R., Park, Y., Jeong, S. Y., Song, Y. J., Hwang, Y. H., Lee, J., Chi, Y., Wang, S.-F., Jeon, Y., Huh, C.-H. & Choi, K. C. *ACS Appl. Mater. Interfaces* 15, 57415–57426 (2023).

Modifications to the revised manuscript in lines 413–417 of the Result section to show why we used 800 nm device, clearly.

To assess the effects of OLED emission wavelength and angular distribution for non-invasive phototherapy, transdermal transmission was analyzed using four OLED device types, including a cavity red OLED with a peak at 640 nm, a non-cavity and a cavity NIR OLED with peak at around 730-740 nm, and a cavity NIR OLED with peak at 800 nm **(Supplementary Fig. 12).**

Modifications to the revised manuscript in lines 439–446 of the Result section to describe benefits of tuned OLED.

At normal emission, the band-integrated photon radiance within the region was approximately 2.4 times greater for the cavity NIR OLED than for the non-cavity device. This tuning can provide to greater photon delivery at the hDPCs activation peak near 730 nm, compared with the non-cavity device, thereby enhancing photostimulation under equivalent dose condition, as shown in **Figure 5d**. An analysis relating hDPCs activation to the OLEDs' optical properties is provided in the *in vitro* section.

Reviewer's comment 2) All validation was performed using 2D hDPC monolayers. However, in vivo hair follicles reside within a 3D dermal environment and are exposed to vasculature, hormones, and other cell types. How do you account for the translational gap between 2D in vitro data and actual follicular behavior?

RESPONSE

We thank the reviewer for raising the important issue of the translational gap between 2D *in vitro* assays and the complex in vivo follicular environment.

In this work, we employed *in vitro* assays to demonstrate that irradiation from our customized NIR OLED significantly reduced premature senescence in dermal papilla (DP) cells and maximized their anti-aging response. These assays offered a controlled setting in which OLED light directly interacted with DP cells without the influence of intervening tissue layers. We fully recognize that the *in vivo* follicular niche is a three-dimensional system in which multiple intrinsic and extrinsic factors—including melanin, water content, vasculature, endocrine cues, and diverse neighboring cell types—modulate both light propagation and follicular responses. We also note that DP cells naturally adopt a 3D spheroidal organization *in vivo*. Interventions that enhance DP cell activity in 2D culture, such as PBM, are expected to further potentiate follicle-inductive capacity when applied in more physiologically relevant 3D spheroid or organoid models, consistent with prior reports that three-dimensional reprogramming restores hair-inductive properties in human dermal papilla cells.[1]

Thus, although structural and microenvironmental differences exist between culture systems, the beneficial effects observed in vitro are consistent with those obtained in more physiologically relevant 3D or tissue-based models.

To further, we agree that translating *in vitro* effects to real skin is critical. However, previous researches have provided bridging evidence to address the gap between *in vitro* and *in vivo* contexts. For instance, in *ex vivo* human follicle culture, 650 nm red light enhanced follicle proliferation and delayed catagen progression, and clinically, LLLT devices significantly improved scalp hair growth in androgenetic alopecia.[2] These concordant findings suggest that mechanisms observed *in vitro* can translate to real follicles when adequate energy delivery is achieved. Furthermore, bridging studies show that improving DP cell health *in vitro* correlates with better follicle performance *in vivo*: rejuvenating aged DP cells with exosomes reduced senescence markers and restored inductive genes in vitro, and those treated cells enhanced hair-follicle regeneration in patch assays,[3] which are *in vivo* experiments performed in nude mice

to assess whether transplanted cells retain or regain their hair-inductive capacity.

We believe that such evidence reinforces that the anti-senescence activity of customized NIR OLED irradiation demonstrated in vitro has translational relevance *in vivo*.

References

[R1] Higgins, C.A., Chen, J.C., Cerise, J.E., Jahoda, C.A.B., & Christiano, A.M. *PNAS*, 110, 19679–19688 (2013).

[R2] Yang, K., Tang, Y., Ma, Y., Liu, Q., Huang, Y., Zhang, Y., Shi, X., Zhang, L., Zhang, Y., Wang, J., Zhu, Y., Liu, W., Tan, Y., Lin, J. & Wu, W. Annals of Dermatology, 33, 553–561 (2021).

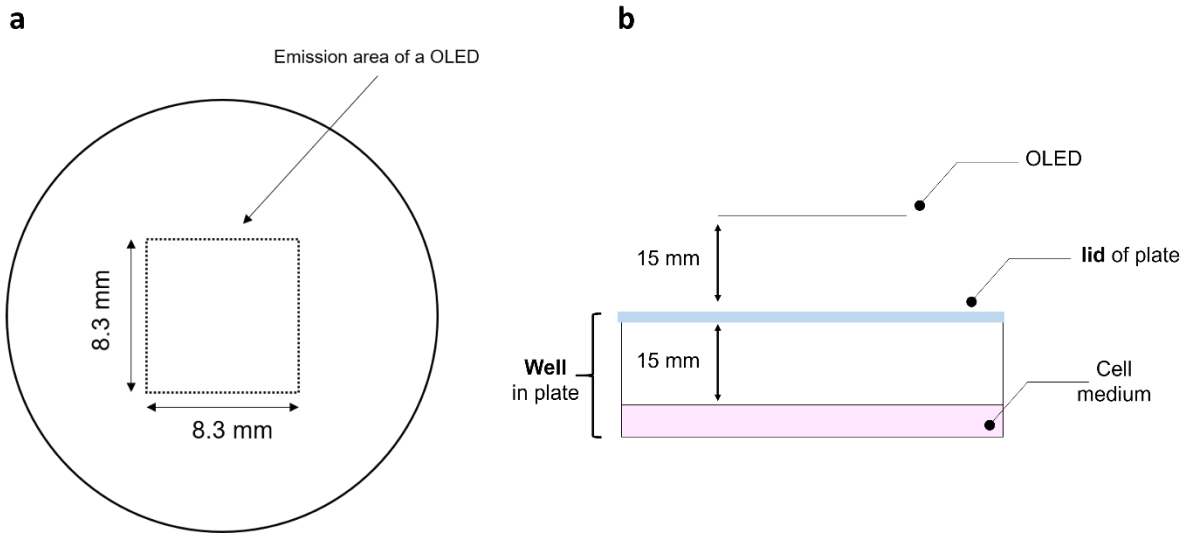
[R3] Liu, F., Liu, S., Luo, X., Fan, Z., Huang, S., Deng, F., Liu, H., & Shi, G. Experimental Dermatology, 32, 1646–1657 (2023).

<u>Reviewer's comment 3)</u> The authors claim the cavity NIR OLED is superior, yet the non-cavity NIR showed greater hDPC migration after 16 hours. How do they reconcile this observation with their main claim of improved performance via cavity tuning? Could this be related to angular distribution or unintended dose differences?

<u>RESPONSE</u>

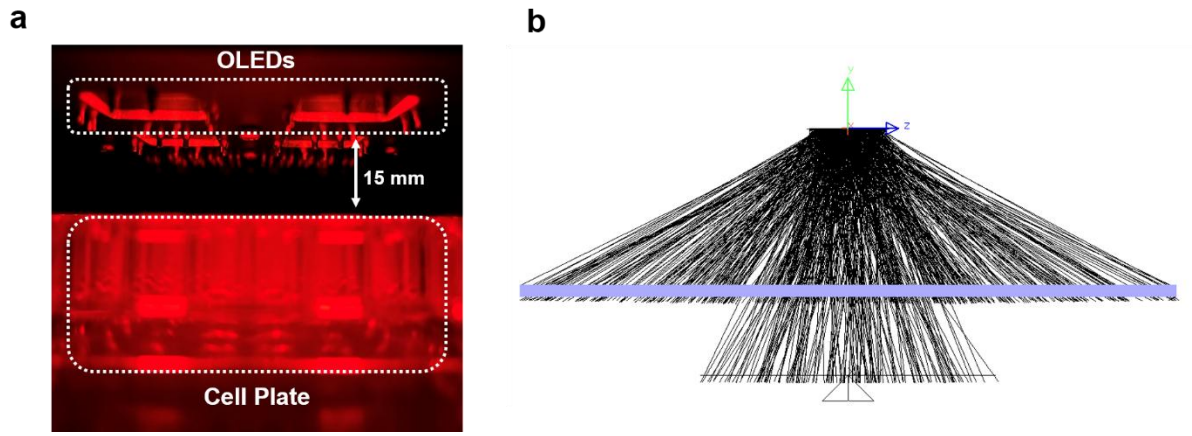
We appreciate the reviewer's insightful comment. To address the possibility that the greater hDPC migration observed for the non-cavity NIR OLED after 16 h might be attributable to angular emission or unintended dose differences, the *in-vitro* irradiation geometry was reproduced identically in a Monte Carlo model and the energy delivered to the cell medium at the receiving surface was quantified.

- **Monte Carlo Replication of the *In Vitro* Irradiation Geometry**



FigR.7 | Schematic of the in vitro experimental setup. a, Top view of the set-up. **b,** Cross-sectional side view of the setup.

To mimic the *in vitro* configuration, the irradiation geometry was reproduced in a Monte Carlo model, identical to our in vitro environment. In this model the OLED-to-cell plate distance was approximately 15 mm, a transparent lid acted as an additional optical interface to prevent particulate contamination, and the well was filled with cell medium corresponding to ~15 mm vertical distance from the lid to the medium surface**. (FigR.7a, b)**



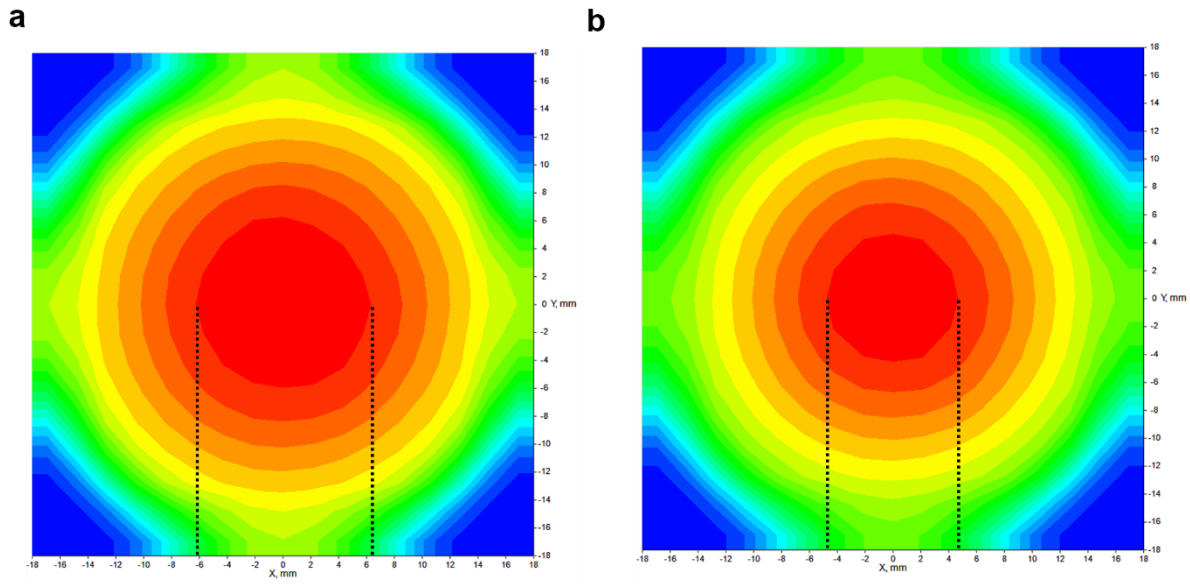
FigR.8 | Monte-Carlo simulation to validate *in-vitro* test. a. Side view of environment of *in vitro* test.**, b.** Monte-Carlo simulation for *in vitro* test.

■ **Angular-Resolved Dose Comparison Between Cavity and Non-Cavity OLEDs**

To analyze the dose delivered to the cell medium at the receiving surface, the angular emission profiles of cavity and non-cavity OLEDs were incorporated into the Monte Carlo framework **(FigR.8)**. When the receiving surface was defined as the full well (diameter 35 mm), contour mapping indicated a broader energy spread for the non-cavity device (effective illuminated diameter ~6.0 mm, as shown in **FigR.9a**) relative to the cavity device (~4.5 mm, as shown in **FigR.9b**), consistent with the non-cavity's more diffuse, super-Lambertian emission.

However, the biological readout was restricted to an orthogonally aligned cell area. The emitting surface measured 8.3 × 8.3 mm², and the analyzed area of cell medium was same. In this study, the analysis of cell activation following OLED irradiation was confined to cells located within this predefined orthogonal region. Under these conditions, the effective irradiance at the cell layer was 0.06 mW cm^{-2} (2% of the emitting-surface radiant intensity, 3mW cm^{-2}), corresponding to a delivered energy of 0.052 J during 20 min of continuous irradiation (0.072 J cm^{-2}).

As a result, the normal-direction component of each OLED—whose emission wavelength was customized by the microcavity—was dominantly delivered to the cells. The configuration showed dose equivalence within the orthogonal region across device types.



FigR.9 | Simulated irradiance profiles in the cell culture medium. a, Non-cavity NIR OLED source**. b,** Microcavity-tuned NIR OLED source**.**

■ Conclusion

The observed differences are therefore not attributed to unintended angular dose contributions but are more likely due to short-term cellular responses that do not fully reflect the advantages of cavity tuning. It is speculated that migration assays might be involved variability, as scratches are produced manually, potentially introducing differences in wound width and uniformity.

Nevertheless, a substantial enhancement in migration was observed in the irradiated OLED groups compared with the non-irradiated control group, indicating that light exposure exerted a strong pro-activating effect under the stated conditions. Also, the cavity OLED was designed to enhance spectral alignment with the CCO absorption band and to deliver higher irradiance at the therapeutic wavelength. These benefits become more apparent in senescence suppression. We have clarified this reason in the revised manuscript to avoid misinterpretation.

Modifications to the revised manuscript in lines 510–531 of the Result section

For each OLED, the emitting-surface radiance was set to around 10 W m^{-2} sr^{-1} for continuous irradiation during 20 minutes. Analysis of cell activation was limited to an orthogonally aligned square region, where the emitting surface measured 8.3 × 8.3 mm^2 and the area matched the beam size of OLED **(Supplementary Fig. 17b)**.

To verify the light dose delivered to the cell medium, a Monte Carlo simulation that reproduced the in vitro configuration was performed. Because dose delivery to away from emitting surface depends on the OLED angular emission profile, the receiving surface was defined as the full well with a diameter of 35 mm. The simulation indicated an energy spread for the non-cavity NIR OLED, with an effective illuminated diameter of approximately 6.0 mm as shown in **Supplementary Figure 17c.** The cavity NIR OLED exhibited an effective illuminated diameter of approximately 4.5 mm (**Supplementary Fig. 17d)**. This observation is consistent with the more diffuse super Lambertian emission of the non-cavity device. However, to ensure that in vitro outcomes were obtained from cells exposed to light, the analysis area was fixed to match the beam size and aligned orthogonally to the OLED.

Under these conditions the effective irradiance at the cell medium was 0.06 mW cm^{-2}, which is approximately 2% of the emitting surface power density of 3 mW cm^{-2}, and this corresponded to a delivered irradiance of 0.072 J cm^{-2} during 20 min of continuous exposure. This configuration allowed to compare cellular responses under same dose to red versus NIR emission and to evaluate the impact of NIR spectral bandwidth.

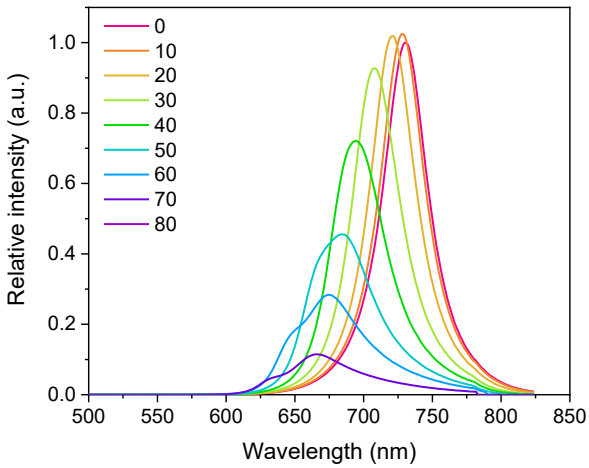
Reviewer's comment 4) With such spatial and angular variations in emission, how do you control for accurate irradiance delivery over curved, irregular scalp surfaces? Are there active or passive dosimetry mechanisms built into the textile?

RESPONSE

We appreciate the reviewer's thoughtful comment on the potential role of passive dosimetry mechanisms. Such functionality would indeed be highly valuable for wearable systems; however, the current textile OLED platform does not incorporate embedded passive dosimetry features.

As you know, cavity OLEDs inherently exhibit angle-dependent emission characteristics. When applied to curved scalp surfaces, this angular dispersion may lead to minor spectral shifts such that slightly different wavelength components reach the tissue depending on local geometry. We believe that the wearable textile design itself provides a mitigating factor, as the device is highly flexible and enables closing to the scalp via a hat platform without the need for adhesive materials, thereby reducing air gaps and maintaining close contact with the tissue. This intimate skin conformity was a central aspect of our design strategy for textile-based photonic devices.

We acknowledge that angular-dependent spectral variation remains a limitation of microcavity OLEDs **(Supplementary Fig. 12).** Since our study identified 730 nm as the most effective wavelength for follicular activation, maintaining this peak across all emission angles is essential. In the field of phototherapy, cellular activation strongly depends on wavelength; therefore, ensuring spectral stability is particularly important. However, we believe that the limitation of cavity OLEDs could be addressed by integrating a scattering layer (SL) in following research.



Supplementary Fig. 13| Emission spectra of cavity NIR OLEDs as a function of viewing angle.

Shin et al. had shown that introducing SL can reduce angle-dependent spectral shift. Shin et al. reported that an OLED without the SL exhibited a spectral shift of more than 30 nm between 0° and 60°, whereas the SL-equipped OLED reduced this shift to below ~10 nm.[1] In addition, Keum et al. showed that applying RIE treatment to the upper Parylene-C layer can increase scattering without damaging a OLEDs, effectively preventing the blue shift of the emission peak with viewing angle.[2]

Thus, incorporation of scattering technology into our wearable phototherapy device could enable angle-independent emission centered at 730 nm, thereby ensuring consistent delivery of the most effective therapeutic wavelength to hair follicles. To date, such studies have primarily been conducted in the visible spectral range; however, applying the same concept to NIR OLEDs is expected to similarly suppress angular-dependent spectral shifts, ensuring stable emission at therapeutic wavelengths.

References

[R1] Shin, J.-W., Cho, D.-H., Moon, J., Joo, C. W., Lee, J., Huh, J. W., Park, S. K., Han, J.-H., Cho, N. S., Hwang, J., Chu, H. Y., Lee J.-I. *Opt. Lett*. 39, 3527–3530 (2014).

[R2] Keum, C., Murawski, C., Archer, E., Kwon, S., Mischok, A., Gather, M. C. *Nat. Commun*. 11, 6250 (2020).

<u>Reviewer's comment 5)</u> The study attributes effects to CCO activation and ROS signaling, but presents no direct biochemical validation (e.g., ROS quantification, antioxidant gene expression, or ATP production levels). Why was no such mechanistic validation performed?

<u>RESPONSE</u>

We acknowledge the reviewer's concern regarding the absence of direct biochemical validation for the proposed CCO/ROS mechanism. The study was designed to prioritize phenotypic outcomes of customized OLED exposure on cellular senescence, interpreting the results within established photobiological frameworks rather than performing direct ROS or ATP assays.

- **ROS hormesis and attenuation of senescence via CCO activation**

A "Goldilocks" range of ROS—neither too low nor excessive—has been shown to activate adaptive stress-response pathways (mitohormesis).[1] In this context, CCO stimulation by the customized OLED is posited to generate moderate ROS that function as signaling mediators to upregulate protective programs. Contemporary models of aging indicate that mild ROS elevations induce antioxidant defenses and other pro-survival pathways, thereby limiting senescence and supporting cellular fitness. Consistent with this view, beneficial ROS signaling is understood to engage redox-sensitive regulators (e.g., Nrf2 and related factors), augmenting DNA repair capacity, antioxidant enzyme expression, and mitochondrial quality control, with net delay of cellular aging.[2]

- **Custom OLED spectrum, CCO activation, and non-damaging ROS signaling**

The OLED emission spectrum was tuned to coincide with known CCO absorption features, thereby enhancing enzymatic activity. Prior PBM studies reported that specific red/NIR wavelengths are absorbed by CCO chromophores, elevating electron-transport activity and, consequently, mitochondrial ROS production as a signaling cue.[3]

We agree that additional biochemical assays would further refine the mechanism. However, given the established link between cellular activation and ROS production, emphasis was placed on the resultant senescence phenotype rather than intermediate measurements.

References

[R1] Shields, H. J., Traa, A., & Van Raamsdonk, J. M. *Frontiers in cell and developmental biology*, 9, 628157 (2021).

[R2] Heo, J. C., Park, J. A., Kim, D. K., & Lee, J. H. *Scientific reports*, 9, 10114 (2019).

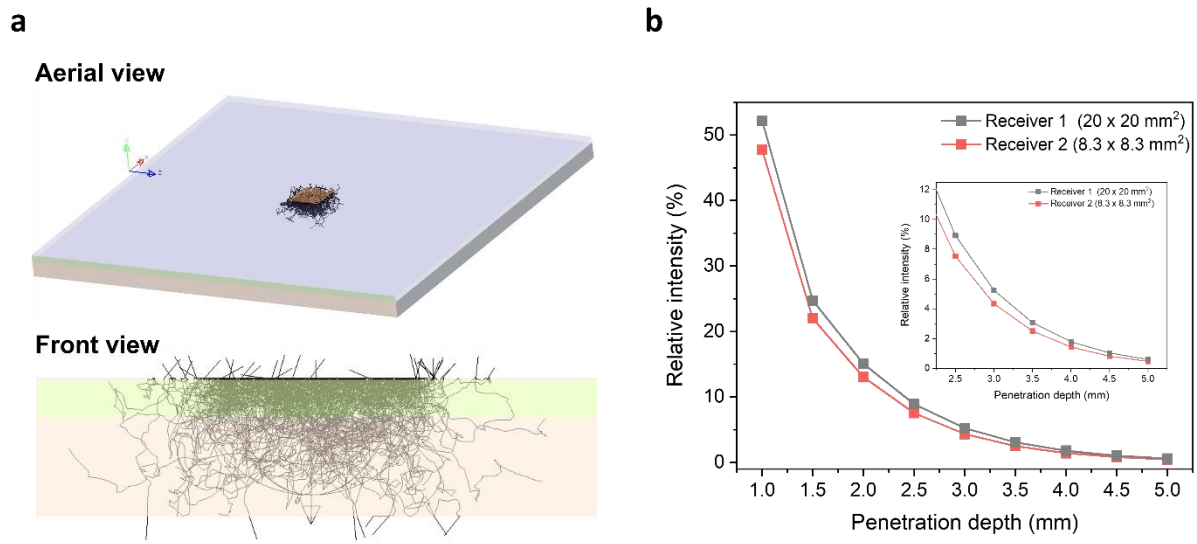
[R3] Cardoso, F. D. S., Barrett, D. W., Wade, Z., Gomes da Silva, S., & Gonzalez-Lima, F. *Frontiers in neuroscience,* 16, 818005 (2022).

<u>Reviewer's comment 6)</u> The pigskin model is useful, but did the authors perform Monte Carlo simulations or tissue-mimicking phantoms to more precisely model photon distribution to the follicle base (~3 mm)? 12% transmission is relative—how much actual photon energy reaches target biological chromophores?

<u>RESPONSE</u>

We sincerely appreciate the reviewer's insightful comment. To complement the pigskin transmission measurements with a more evaluation, Monte Carlo simulations were performed to approximate photon distribution within skin and to assess energy delivery toward the follicle base (3 mm ~).

- **Monte-carlo simulation of photon transport in a skin model**



Supplementary Fig. 14 | Monte Carlo simulation of photon transport and depth-dependent power density distribution. a, Monte Carlo simulation setup. An OLED (8.3 × 8.3 mm²) was placed on the skin surface. **b,** Depth-dependent relative intensity. Grey indicates the maximum power density within the receiver plane, and red indicates the area-averaged power density.

In this model, the epidermis, dermis, and subcutaneous fat layers were defined with layer-specific refractive indices scattering coefficients (μ_s), and anisotropy factors (g), all set as wavelength-dependent values from the literature.[1] The OLED emission source was defined as an 8.3 × 8.3 mm² square emitter, placed in direct contact with the epidermal surface. To avoid edge artefacts, the simulated skin area was chosen to be larger than the emitting area

(Supplementary Fig. 14a). Planar receivers were placed orthogonally beneath the epidermal surface at depths of 1−5 mm at 0.5 mm intervals (8.3 × 8.3 mm², same with emitting area). At each plane, the irradiance was tallied and normalized to the input, enabling relative intensity analysis across depths. The ratio of receiving-surface irradiance to the emitting-surface irradiance was quantified as 4.3% at 3.0 mm, 1.4% at 4.0 mm, and 0.5% at 5.0 mm, indicating that sufficient photon energy can still be delivered to the follicular niche (~3 mm) to support cellular activation despite strong attenuation **(Supplementary Fig. 14b).** In addition, contour maps revealed progressive lateral broadening with increasing depth due to multiple scattering; nevertheless, dose delivery remained predominantly concentrated along the axis orthogonal to the OLED emitting area **(Fig R. 10).**

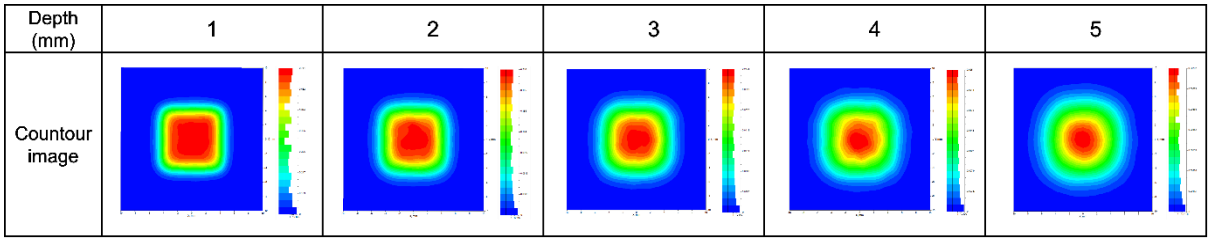


Fig R. 10 | Contour maps of irradiance at receiver planes located 1.0–5.0 mm beneath the epidermal surface

■ Explaining the discrepancy between pigskin transmission and the simulation

Two experimental factors are considered to account for the higher transmission observed in pigskin (~12%) relative to the simulation (~4.3%). First, the pigskin samples were desiccated prior to measurement, which reduced water-mediated absorption. Second, only the epidermis–dermis slab was used (i.e., no subcutaneous fat layer), eliminating an additional refractive-index boundary and a layer that would otherwise contribute to internal reflection and multiple scattering. These differences show the reason of high measured transmission level relative to the multilayer Monte Carlo simulation based on real skin model.

■ Conclusion

Notably, our in vitro measurements showed an emission-to-reception power ratio of approximately 2%. Despite the modest dose (0.052 J, corresponding to 0.043 mW for 20 min), we observed clear enhancements in dermal papilla cell migration and anti-senescence responses (see our response to your **Comment 3**). Consistent with these data, the simulations indicate that a NIR OLED in direct skin contact can deliver sufficient photon energy to the follicular niche to stimulate dermal papilla cell activation.

References

[R1] Shimojo, Y., Nishimura, T., Hazama, H., Ozawa, T., & Awazu, K. *Journal of biomedical optics,* 25, 045002-045002 (2020).

Modifications to the revised manuscript in lines 463–479 of the Result section for including simulation results.

To validate transmittance of the NIR OLED light in real skin, Monte Carlo simulations were performed to measure photon delivery from a skin conformal wearable near infrared OLED to the hair follicle region. In this model, the epidermis, dermis, and subcutaneous fat layers were defined with layer-specific refractive indices scattering coefficients (μ_s), and anisotropy factors (g), all set as wavelength-dependent values from the literature.[32] The emission source was set an 8.3 × 8.3 mm² square that was placed in direct contact with the epidermal surface **(Supplementary Fig.15a)**. Planar receivers were positioned normal to the surface at depths from 1.0 mm to 5.0 mm. The ratio of receiving surface irradiance to power density of emitting surface was 4.3% at 3.0 mm, 1.4% at 4.0 mm, and 0.5% at 5.0 mm **(Supplementary Fig.15b)**.

Simulated transmission was lower than the measured value in porcine skin. The difference was attributed to two features of the experimental setup. The skin was dried before measurement, which reduced absorption by water. In addition, the samples consisted only of epidermis and dermis, whereas the model included epidermis, dermis, and subcutaneous fat. However, the receiving ratio at depths of 3 to 4 mm was similar to that in our *in vitro* setup, which showed a PBM effect under OLED irradiation as described in the below section.

Reviewer's comment 7) Has the team quantified how the refractive index mismatch between parylene-C and human skin affects photon loss via internal reflection or scattering? Could this be mitigated with intermediate index-matching layers?

RESPONSE

We appreciate the reviewer's insightful comment regarding refractive index mismatch at the device–tissue interface. Indeed, differences in refractive index can introduce photon loss through reflection and scattering, and this is an important factor to consider in wearable photonic systems. Accordingly, the magnitude of photon loss arising from the refractive-index mismatch was quantified using the Fresnel reflection equation.

- **Fresnel analysis of refractive index mismatch and photon loss**

At the air–skin interface, photon loss can be estimated using the Fresnel reflection formula: where n_1 and n_2 are the refractive indices of the two adjacent media. For air (n=1) in contact with epidermis of skin (n≈1.44), the reflection at normal incidence is:

$$R_{air-skin} = \left(\frac{1.00 - 1.44}{1.00 + 1.44}\right)^2 \approx 0.033, (3.3\ \%)$$

Considering the refractive-index mismatch at the air–skin boundary, Fresnel reflection is expected to contribute only a modest loss at normal incidence. In the NIR region, taking the skin refractive index as n≈1.44,[1] the normal-incidence Fresnel reflection at the air–skin interface is 3.3%. This represents a modest reduction, and the effect is considered relatively minor in the context of overall light delivery to the tissue. Consequently, while an air gap does introduce inevitable reflection loss, its contribution to the overall transmission is relatively small and does not significantly compromise photon delivery to the follicular region.

- **Potential role and limitations of index-matching layers**

Introducing an intermediate layer with a refractive index close to skin (n≈1.4–1.5) between parylene-C and tissue could reduce internal reflection within the OLED stack and improve light outcoupling.

Case 1 — w/o index-matching layer: parylene-C (1.65) ~ air (1.00) ~ skin (1.44)

$$R_{parylene-C\sim air} = \left(\frac{1.65 - 1}{1.65 + 1}\right)^2 \approx 0.0602, (6.02\ \%)$$

$$R_{air\sim skin} = (\frac{1.00 - 1.44}{1.00 + 1.44})^2 \approx 0.033, (3.3\ \%)$$

Under the assumption that multiple reflections in the intermediate region are incoherent, the total reflectance (R_{total}) can be computed using the following expressions:

$$R_{total} = (0.0602)^2 + (1 - 0.0602)^2 \frac{0.033}{1 - 0.0602 \times 0.033} \approx 0.089, (8.9\ \%)$$

Case 2 — with an index-matching layer: parylene-C (n = 1.65) ~ index-matching polymer (n ≈ 1.5) ~ skin (n = 1.44)

$$R_{parylene-C\sim index-matching} = (\frac{1.65 - 1.5}{1.65 + 1.5})^2 \approx 0.0023, (0.23\ \%)$$

$$R_{air\sim skin} = (\frac{1.5 - 1.44}{1.5 + 1.44})^2 \approx 0.0042, (0.042\ \%)$$

So, R_{total} is:

$$R_{total} = (0.0023)^2 + (1 - 0.0023)^2 \frac{0.0042}{1 - 0.0023 \times 0.0042} \approx 0.004, (0.4\ \%)$$

If a fully adhesive, index-matching layer were applied to eliminate any air gap between the device and skin—so that the interface transitions as parylene-C (n≈1.65) → intermediate layer (n≈1.5) → skin (n≈1.44)—the interfacial Fresnel loss would fall to <0.5%, yielding highly efficient photon delivery. Nevertheless, this design brings a trade-off: such adhesive layers may pull or damage residual hair upon device removal, limiting practicality in wearable applications.

In summary, an air gap at the device–skin interface introduces photon loss. Nevertheless, Fresnel analysis indicates that, at normal incidence, this loss is limited to approximately 3–4% and is therefore minor. Although additional index-matching interlayers could further reduce the loss, the risk of residual hair damage imposes significant constraints for users. Accordingly, our device is expected to enable non-invasive delivery of photons to the follicular region with minimal interfacial losses.

References

[R1] Ding, H., Lu, J. Q., Wooden, W. A., Kragel, P. J., & Hu, X. H. *Physics in Medicine & Biology*, 51, 1479 (2006).

<u>Reviewer's comment 8)</u> Your microcavity devices show ~40 nm FWHM. Some studies suggest broader bandwidths (~100 nm) can stimulate a wider range of cellular photoreceptors. Could overly narrow spectral targeting reduce holistic tissue activation?

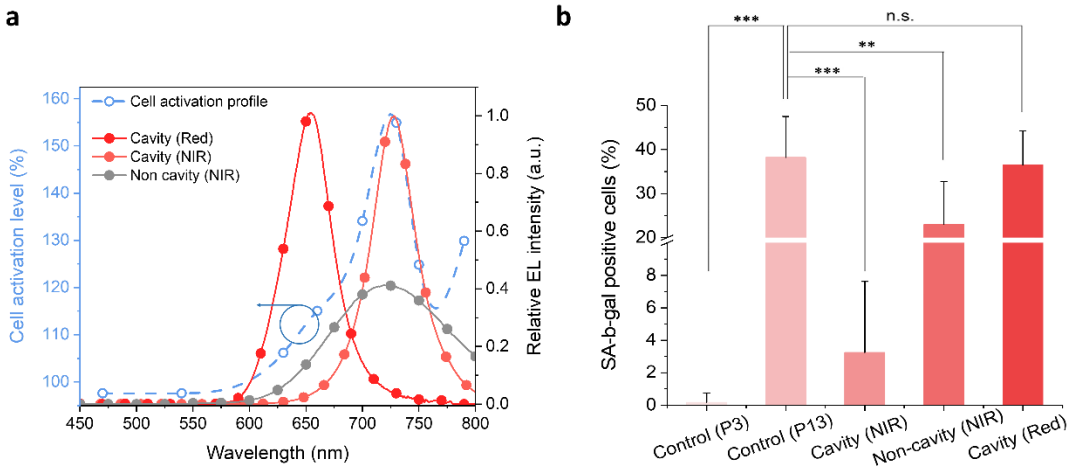
<u>RESPONSE</u>

We appreciate the reviewer's insightful question. Our view is that, for PBM in which mitochondrial CCO dominates the response, spectral precision that concentrates photons within the CCO-effective window is advantageous over broadband emission that spreads power across less responsive wavelengths.

- **PBM effect follows cell activation spectrum**

PBM efficacy depends on how many photons are absorbed by relevant chromophores, not on total radiant power alone. In practical terms, the relevant figure of merit is the spectral photon flux density delivered to tissue and its overlap with the cellular action spectrum.

The cellular action spectrum is wavelength-dependent, so concentrating photons near its peak increases the biological response. Under same irradiance and dose conditions, a spectrum that places more photons where absorption is highest yields a larger cellular response. A ~100 nm broadband source distributes the same total power over a wider span, reducing photon density in the optimal wavelength region (around 730 nm). By contrast, a customized OLED with a ~40 nm FWHM spectrum centered in the CCO-mediated cellular action-spectrum region increases photon density at the wavelengths most relevant for mitochondrial activation while keeping the total dose unchanged **(FigR.11a)**. Notably, the non-customized and customized OLEDs had nearly identical peak wavelengths at ~730 nm, but the spectral peak intensity (photon density) at 730 nm was ~2.5× higher for the customized microcavity device.



FigR.11 | PBM performance with customized vs non-customized OLEDs. a, Overlay of the cellular action spectrum for proliferation with the EL spectra of the cavity OLED (red and NIR) non-cavity OLED (NIR) under same radiance. **b,** Cellular senescence after irradiation with each OLED at same dose.

In fact, our *in vitro* data support 730 nm targeting. In our assays, DP cells exhibited the strongest activation after irradiation with the cavity NIR OLED, with the most pronounced anti-senescence effects, when compared to the red and non-customized OLED spectra under matched total irradiance and dose **(FigR.11b)**. Moreover, PBM efficacy followed the order Red < non-cavity NIR < cavity NIR, in agreement with the cell-activation profile. Thus, the greater photon flux delivered at the CCO-effective peak explains the amplified cellular response in the customized condition.

■ Influence of narrow spectral bandwidth to cell activation

PBM is associated with CCO activation. CCO contains metalloprotein centers (CuA, heme a, heme b) with distinct activation wavelengths. Comprehensive activation of CCO therefore requires stimulation that encompasses the entire complex.[2,3] A narrow-band spectrum may selectively excite only certain components and thus may be insufficient to induce overall CCO activation, potentially reducing PBM effects.

PBM efficacy has not been researched by narrowing FWHM while maintaining an identical peak wavelength. Thus, we think additional investigation is required to evaluate this parameter.

References

[R1] Ding, H., Lu, J. Q., Wooden, W. A., Kragel, P. J., & Hu, X. H. *Physics in Medicine & Biology*, 51, 1479 (2006).

[R2] Karu, T. I., & Kolyakov, S. F. *Photomedicine and Laser Therapy*, 23, 355-361 (2005).

[R3] Hamza, I., & Gitlin, J. D. *Journal of bioenergetics and biomembranes*,34, 381-388 (2002).

Modifications to the revised manuscript in lines 443–450 of the Results section.

At normal emission, the band-integrated photon radiance within the region was approximately 2.4 times greater for the cavity NIR OLED than for the non-cavity device. This tuning can provide to greater photon delivery at the hDPCs activation peak near 730 nm, compared with the non-cavity device, thereby enhancing photostimulation under equivalent dose condition, as shown in **Figure 5d**. An analysis relating hDPCs activation to the OLEDs' optical properties is provided in the *in vitro* section.

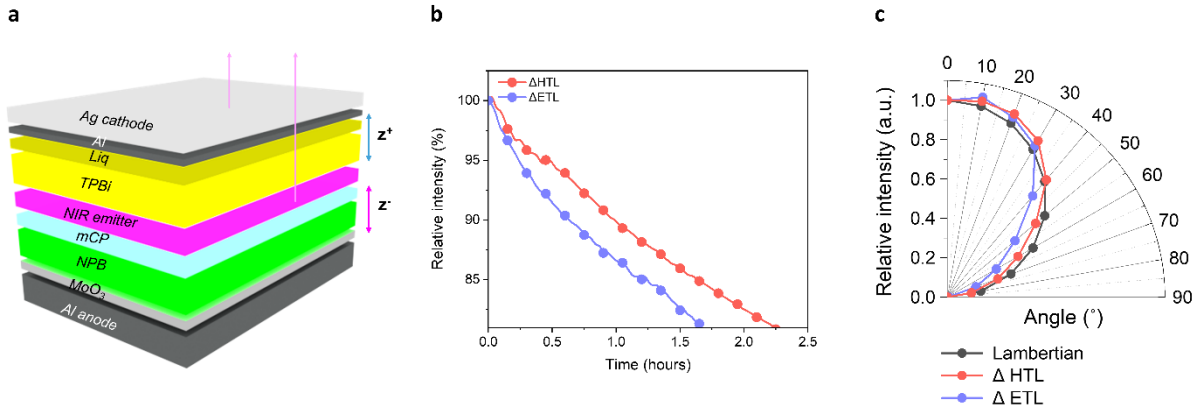
<u>Reviewer's comment 9)</u> While HTL-tuned microcavity devices show higher EQE than ETL-tuned ones, did you quantify trade-offs in carrier balance, recombination zone position, or angular intensity losses at oblique angles? How does the angular spectral stability compare under real-world usage conditions?

<u>RESPONSE</u>

We appreciate the reviewer's interest in our work. As noted by the reviewer, carrier balance, recombination-zone (RZ) position, and angular intensity are important parameters in OLED development. Trade-offs were quantified by comparing operational lifetime and the angle-resolved intensity profile. Two device sets with an identical optical cavity length were fabricated; only the distribution of the organic thickness was varied to realize HTL-tuned and ETL-tuned stacks **(FigR.12a)**.

- **Trade-offs in each parameter of OLEDs**

To assess carrier balance and RZ position, operational lifetime was measured under continuous constant-current drive with matched initial radiance across all devices. A faster radiance decay was observed for ETL-tuned devices than for HTL-tuned devices **(FigR.12b).** This trend is consistent with carrier imbalance and an RZ pinned near the EML/ETL interface in the ETL-tuned case, which can increase interfacial non-radiative loss. Considering the mobility asymmetry—hole transport in typical HTLs exceeding electron transport in ETLs—placing the additional thickness on the HTL side rebalanced the carrier fluxes,[1] broadened and centered the RZ within the EML, and was associated with improved operational stability under identical optical loading.



FigR.12 | Comparison of HTL-tuned and ETL-tuned microcavity OLEDs at identical cavity length. a, Schematic of the architecture in which the total optical cavity length is held constant while the organic thickness is allocated on the HTL-tuned or the ETL side. **b,** Operational lifetime measured under continuous, constant-current drive at a matched initial radiant intensity. **c**, Angle-resolved radiant-intensity profiles.

Angle-resolved measurements from 0° to 80° were performed to examine oblique losses. A steeper decrease in intensity at oblique angles was observed for ETL-tuned microcavities, particularly beyond ~40–50° **(FigR.12c)**. When the RZ is located closer to the EML/ETL interface, the effective optical path to the output mirror (thin Ag cathode) is increased and the angle-dependent cavity phase is strengthened, owing to the cavity phase being proportional to the distance between the output electrode and the RZ. These effects are consistent with microcavity interference theory and are accounted for the larger decrease in intensity at oblique angles. Additionally, a longer optical path results in greater absorption, thereby reducing the light intensity.

Therefore, in HTL-tuned devices, an RZ located closer to the output mirror mitigates these effects, thereby reducing internal optical losses and enabling stronger light emission.

■ **Angular spectral stability under real-world usage conditions**

Customized NIR OLED (HTL-tuned) in this study were observed to exhibit a decrease in intensity with viewing angle; however, the angular distribution remained close to Lambertian. In contrast to laser emission, which occurs predominantly along the surface normal, the near-Lambertian emission of OLEDs is advantageous for non-invasive phototherapy in the following respects.

① Dose uniformity under misalignment and motion

A broadly distributed angular profile tends to support more uniform fluence on curved tissue when the emitter is tilted or laterally displaced. Sensitivity to pointing error is reduced relative to directional sources, which can improve repeatability across sessions in wearable use.

② Mitigation of hot spots and thermal load

The absence of narrow angular lobes lowers the likelihood of localized over-irradiance and associated surface heating, facilitating compliance with exposure limits at a given average dose.

③ Robustness to air-gap and standoff variations

For near-Lambertian fields, attenuation of dose with increasing emitter–tissue distance is gradual, maintaining useful fluence across 0–5 mm air gaps that are typical of textile wearables, whereas narrow-beam sources often show a steeper on-axis decrease at small tilts.

Modifications to the revised manuscript in lines 259–265 of the Results section.

To compare the two tuning strategies, the optical cavity length was maintained constant by applying an identical thickness increment to either the HTL or ETL. In the HTL-tuned OLED, the NPB layer was increased by 37 nm relative to the conventional recipe, which adjusted the optical path and positioned the main EL peak at 730 nm. Using this optimized condition as a reference, the ETL-tuned OLED was fabricated by extending the TPBi layer by the same 37 nm, thereby preserving an equivalent cavity length across both configurations.

Modifications to the revised manuscript in lines 280–285 of the Results section.

Because hole transport in NPB exceeds electron transport in TPBi, adjustment of the NPB thickness, in part owing to the carrier mobility imbalance,[27] positioned the recombination zone more effectively within the emissive layer, to reduce the proportion of non-radiative interfacial exciplex. In fact, the HTL-tuned OLED exhibited slightly improved operational lifetime compared with the ETL-tuned device **(Supplementary Fig. 4b)**.

Reference

[R1] Rhee, S. H., Nam, K.b., Kim, C. S., Song, M., Cho, W., Jin, S. H., & Ryu, S. Y. *ECS Solid State Letters*, 3, R19 (2014).

Reviewer's comment 10) The manuscript claims 'markedly superior efficacy' of the textile-integrated NIR OLED system compared to conventional phototherapy methods. However, there is no quantitative benchmarking against existing commercial or clinically validated devices (e.g., LLLT helmets like iRestore, HairMax, or LG Pra.L Medi Hair). Can the authors provide a controlled, side-by-side comparison of their device's therapeutic outcomes — such as hDPC migration rates, senescence reduction, and transdermal photon flux — relative to these established devices under matched irradiance and exposure conditions? Without such benchmarking, how can superiority over current clinical standards be substantiated?"

RESPONSE

We thank the reviewer for the insightful comment. A head-to-head clinical comparison against specific commercial systems was difficult to perform in this study because key device-level specifications are not publicly disclosed, operating conditions differ across products, and PBM efficacy evaluation models differ across studies, making precise comparative analysis difficult.

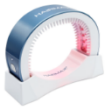
- **PBM advantages**

However, to demonstrate the superior PBM efficiency of the customized NIR OLED in this study, experiments were conducted with the same type of light source, the same distance between the cell culture and each OLED, the same emitting-area size, the same exposure time, the same surface irradiance on the cell medium, and the same total dose; the independent variables were limited to (i) the central wavelength and (ii) the full width at half maximum (FWHM). Within this framework, a red band representative of commercial LLLT devices such as iRestore, HairMax, and LG Pra.L Medi Hair was compared with near-infrared emissions, including a cavity-tuned spectrum centered at 730–740 nm and broader non-cavity NIR bands. Under matched irradiance, human dermal papilla cells (hDPCs) exhibited photostimulation across the red–NIR range, and the cavity-tuned 730–740 nm spectrum yielded the greatest activation at the same dose, consistent with alignment with the hDPC activation spectrum.

- **Wearable design advantages**

As summarized in the **TableR.2**, commercial low‑level light therapy devices such as iRestore, HairMax, and LG Pra.L Medi Hair adopt rigid helmet or hair‑band form factors populated with discrete LEDs/lasers whose emitting areas are typically reported at the device level but not at the source level (often in the tens of micrometres for individual laser apertures). These architectures concentrate light into sparse beam spots across the scalp and require a hard shell to maintain source positioning, which constrains comfort, conformability, and uniformity during use. In contrast, the presented textile-based NIR OLED integrates a contiguous,

millimetre-scale emitting area directly onto a flexible polyester textile and is demonstrated in a hat-type platform. This configuration enables continuous, areal emission that conforms to scalp curvature, reduces local hot-spotting, and improves irradiance uniformity across targeted regions.

Characteristics of phototherapy devices for hair-loss treatment				
Characteristics	Devices			
	iRestore[1]	HairMax[2]	LG Pra.L[3]	This work
Image				
Platform	Helmet	Hairband	Helmet	Hat
Light source	LED and Laser	Laser	LED and Laser	OLED
Wavelength	625, 655 and 680nm	655 nm	630, 655 and 660 nm	730 nm
Emitting area	Not reported (usually, 50~100 μm scale)			• 8.3 x 8.3 mm^2 • 300 **nm**
Use Environment	Home-use	Home-use	Home-use	Unrestricted
Flexibility	Rigid	Rigid	Rigid	Flexible
Uniformity	Poor	Poor	Poor	Good

TableR.2 | Comparison of commercial phototherapy devices for hair loss treatment.

Furthermore, from a wearable-use perspective, the textile form factor offers additional design advantages. First, flexibility of the emissive substrate and interconnects allows natural deformation during donning, doffing, and head movement without disrupting optical alignment. Second, the platform is not restricted to a rigid shell; integration in hat-type garments permit unobtrusive, day-to-day wear and supports use beyond home settings. Finally, the areal-emission modality of the OLED could be supported scalable coverage by tiling pixels over large regions. These suggest that the textile-integrated NIR OLED platform can be offered wearable-design advantages over commercial devices.

References

[R1] Kim, H., Choi, J. W., Kim, J. Y., Shin, J. W., Lee, S. J. & Huh, C. H. *Dermatol. Surg.* 39, 1177–1183 (2013).

[R2] Leavitt, M., Charles, G., Heyman, E. & Michaels, D. *Clin. Drug Investig*. 29, 283–292 (2009).

[R3] Kim, J. W., Kwon, Y. S., Chang, Y. Y., Hong, S. H., Shin, J. W., Na, J. I. & Huh, C. H. *Medical Lasers: Engineering, Basic Research, and Clinical Application* 9, 150–158 (2020).

Modifications to the revised manuscript in lines 64–87 of the Introduction section

Micro-LED patches offer a more flexible form factor than rigid helmet or home-use phototherapy systems and can improve conformity to skin. However, limitations arise from the patch architecture and the micro-scale emitting area of individual sources. Because attachment typically relies on skin adhesives, patches can inadvertently induce hair traction during application and removal, which is a non-trivial concern for patients with weakened hair follicle anchorage.[10] Moreover, the pixelated point-source nature of micro-LEDs complicates scaling to large treatment areas and tends to produce non-uniform irradiance with local hot spots, thereby limiting dose homogeneity across the scalp. Motivated by these constraints, OLED-based phototherapy device has been suggested. Unlike conventional light sources for phototherapy device, such as LEDs and lasers, OLEDs offer a combination of ultra-thin, flexible form factors and uniform light emission. A OLED-based platform provides large, homogeneous emission and have been reported to induce PBM relevant to hair-loss treatment.[11] However, barriers to day-to-day wearability persist. The platform has been designed for helmet-type configurations, paralleling commercial systems such as iRestore and LG Pra.L Medi Hair, and therefore do not fully exploit core OLED attributes—low mass, thin profiles, and mechanical flexibility.

Furthermore, the light irradiation should be capable of inducing hair growth. The PBM effect depends on the target cell type and wavelength band. Recent studies indicate that human

dermal papilla cells (hDPCs), which play a crucial role in hair regeneration,[12] exhibit enhanced proliferation after exposure to near-infrared (NIR) irradiation compared with red light at the same dose, providing the importance of selecting an optimal wavelength for effective treatment.[13,14]

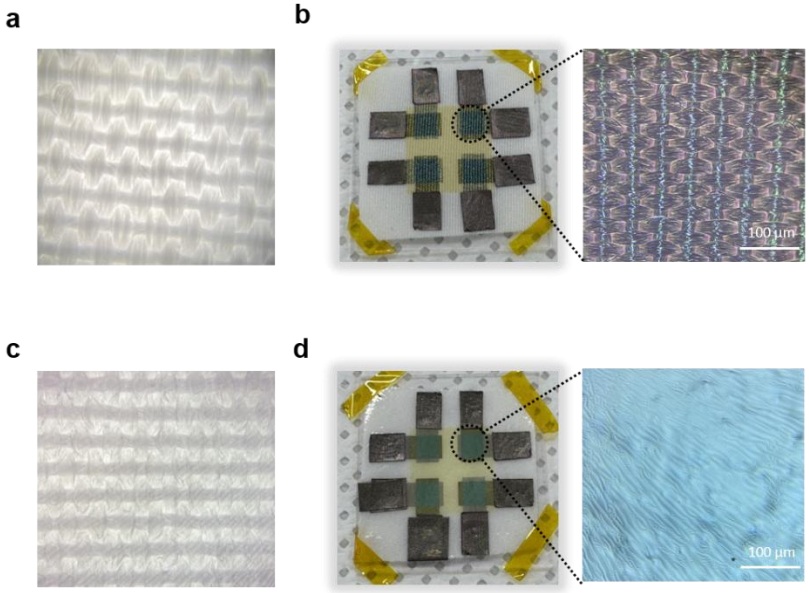
<u>Reviewer's comment 11)</u> OLEDs are known to suffer from current spreading issues and voltage gradients on large substrates. How do you ensure homogeneity of brightness across a large, curved textile interface?

<u>RESPONSE</u>

Thank you for the insightful comment. For phototherapy OLEDs, device-level luminance uniformity is critical because dosing requires consistent irradiance at the specific therapeutic wavelength. We achieve uniformity on the textile platform by (i) applying a CVD-deposited planarization layer formed on glass and transferred to the textile, and (ii) avoiding a single large light source in favor of around 10 mm beam, which consider a balance between skin-penetration depth and OLED stability.

- **Overcoming a roughness of textile through additional planarization layer.**

A planarization film based on parylene-C was deposited by CVD onto a glass carrier and then transferred onto the textile. Owing to the high step coverage of CVD, the planarization film replicated the smoothness of the glass rather than the weave-induced height variations of the textile.[1] In the absence of a planarization layer, OLED deposition followed the inherent roughness of the textile (**FigR.13a, b**), and the resulting devices could not be electrically driven. After introducing the planarization layer, the textile roughness was significantly mitigated, and the subsequently deposited OLED no longer conformed to the underlying texture (**FigR.13c, d**).



FigR.13| Parylene-C planarization to compensate textile roughness. a, Optical microscopy (OM) image of the textile surface before planarization. **b,** OM image of an OLED deposited on a non-planarized textile. **c,** Surface image of the textile after parylene-C planarization. **d,** OM image of an

OLED deposited on the planarized textile.

- **Avoiding large-area gradients of OLED based on trade-off between beam width and OLEDs stability.**

Luminance uniformity issues—often arising from organic-layer deposition non-uniformity and, in cavity OLEDs, from resonance-wavelength shifts with electrode and organic-layer thickness—are intrinsic to large-area OLEDs, even on rigid glass. This issue is not specific to textile platforms. In addition, excessively large emitting areas exacerbate lateral voltage drop and thermal stress, thereby accelerating OLED degradation. However, in our application, this does not impose a practical limitation.

Typically, penetration depth is primarily related to the light wavelength, but it is also influenced by the beam size. For non-invasive phototherapy devices, skin penetration of light was observed to saturate when the beam width exceeded ~10 mm, and this saturation effect persisted up to approximately 40 mm, so further increases in beam size provide no additional benefit.[2] Accordingly, we fabricated and evaluated a single-pixel OLED with an emitting aperture of 8.3 mm × 8.3 mm (beam size ~10 mm). Sample-to-sample spectral variation was minimal (main peak within ~5 nm), indicating negligible organic-layer thickness differences and consistent electro-optical behavior.

On this basis, if a textile device were to array these pixels, it would preserve optical uniformity and maintain non-invasive skin penetration, enabling efficient phototherapy. Furthermore, by limiting the emitting area to such pixel dimensions, localized degradation arising from thermal stress in large-area OLEDs can be mitigated, thereby preventing lifetime reduction.

References

[R1] Cho, H. E., Kim, M. J., Chang, J., An, J., Na, Y., Choi, S., Jeong, S. Y., & Choi, K. C. *npj flexible electronics*, 9, 36 (2025).

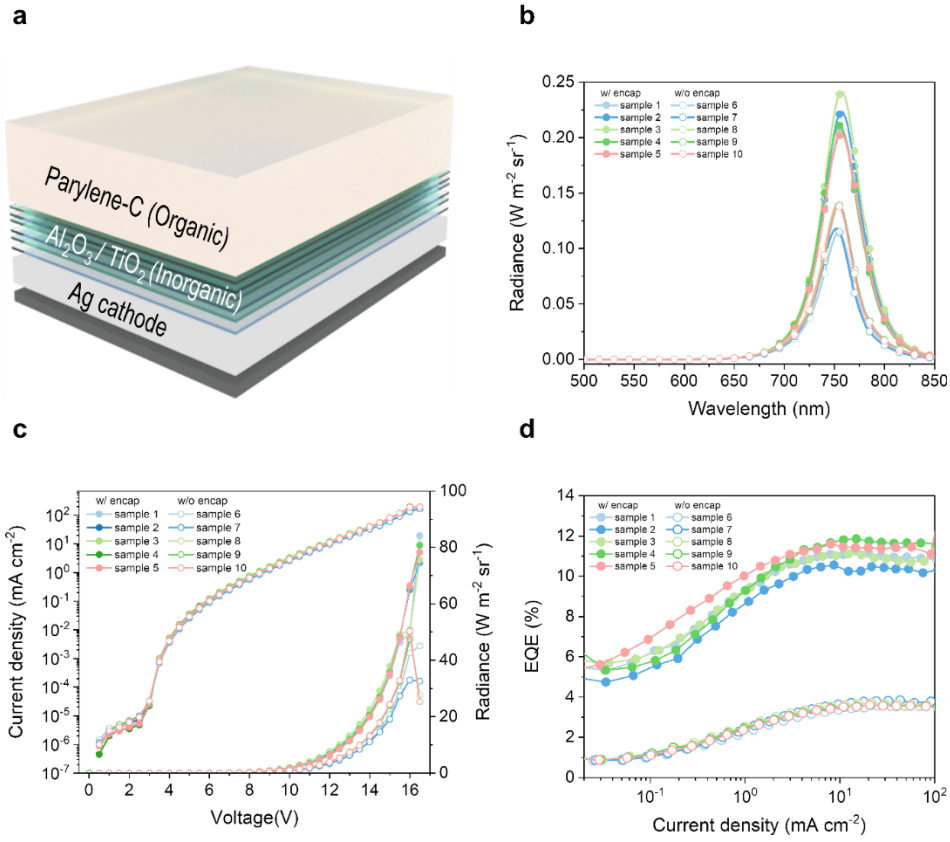
[R2] Ash, C., Dubec, M., Donne, K., & Bashford, T. *Lasers in medical science*, 32, 1909-1918 (2017).

<u>Reviewer's comment 12)</u> How consistent are key performance metrics such as luminance, EQE, FWHM, and turn-on voltage across batches? What is the coefficient of variation in performance across 10+ fabricated devices?

<u>RESPONSE</u>

We appreciate the reviewer's comment regarding the reliability of our dataset. To evaluate the variation of each OLEDs depending on the capping layer, device-to-device variability was quantified by fabricating and characterizing 10 OLEDs.

The variation was computed for electrical metrics (EQE and radiance) and for optical metrics (EL peak wavelength and FWHM). Because visual sensitivity is minimal in the NIR, luminance was not adopted as a primary figure of merit; radiance was analyzed instead **(FigR.14)**. As shown in **Figure 3** of the main text, the performance enhancement induced by deposition of the capping (encapsulation) layer—comprising inorganic and organic sublayers—was verified through batch-to-batch comparison.



FigR.14 | Batch-to-batch performance metrics of the NIR OLEDs a, Schematic of the emitting-side (top-emitting) device stack. **b,** EL spectra of individual devices driven at a same voltage. **c**, Current-density–voltage–radiance (J–V–R) characteristics. **d,** External quantum efficiency (EQE) as a function of current density. For b–d, all devices (n = 10) were measured under identical conditions across batches. (closed symbol: w/ encap, open symbol: w/o encap)

■ Optical characteristics

An average EL main peak of 752.4 nm for devices without encapsulation and 755.6 nm for devices with encapsulation was observed, yielding an approximately 3 nm red shift **(TableR.3)**.

w/ encap	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean
λ_{Peak} (nm)	755	756	757	754	756	755.6
w/o encap	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Mean
λ_{Peak} (nm)	753	751	752	754	752	752.4

TableR. 3 | EL peak wavelength of individual devices and batch mean (n = 10).

The FWHM increased from approximately 39 nm (without encapsulation) to 46.2 nm (with encapsulation), corresponding to an increase of about 7 nm **(TableR.4)**.

w/ encap	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean
FWHM (nm)	46.2	46	46.2	46.3	46.5	46.2
w/o encap	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Mean
FWHM (nm)	39	38.8	39	38.3	38.3	39

TableR.4 | FWHM of individual devices and batch mean (n = 10).

■ Electrical characteristics

J–V characteristics were overall maintained between devices without encapsulation and with encapsulation. However, near the maximum operating voltage, more stable operation was observed for encapsulated devices. Under stress (higher current density), devices without encapsulation exhibited degradation, whereas encapsulated devices did not. The maximum EQE increased from an average of 3.7% to 11.4% after encapsulation **(TableR.5)**.

w/ encap	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean
EQE_{max} (%)	11.25	10.56	11.50	11.86	11.6	11.35
w/o encap	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Mean
EQE_{max} (%)	3.70	3.84	3.70	3.59	3.61	3.69

Table.5 | Maximum EQE of individual devices and batch mean (n = 10).

The maximum radiance increased from 44.8 W m^{-2} sr^{-1} to 78.7 W m^{-2} sr^{-1} after encapsulation **(TableR.6)**

w/ encap	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Mean
$Radiance_{max}$ (w m^{-2} sr^{-1})	84.2	74.6	75.6	80.8	78.3	78.7
w/o encap	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Mean
$Radiance_{max}$ (w m^{-2} sr^{-1})	45.1	33	48.3	47.4	50.3	44.82

Table.6 | Maximum radiance of individual devices and batch means (n = 10).

Additional data were included to reinforce Figure 3 in the manuscript. The revised manuscript was improved with statistical analysis based on inter-sample variation and mean values.

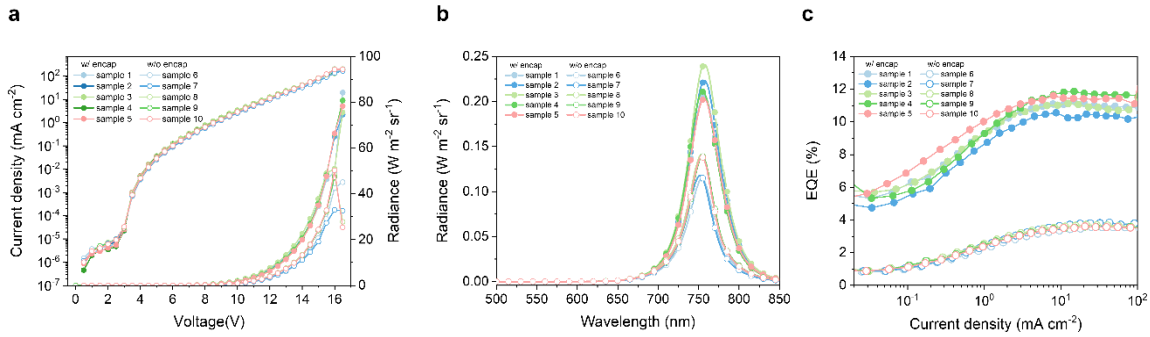
Modifications to the revised manuscript in lines 323–330 of the Results section.

To investigate the influence of the capping layer on device performance, the optoelectronic characteristics of OLEDs were compared with and without the added layer through 10 devices. Integration of the capping layer did not alter the electrical characteristics, as evidenced by unchanged input bias characteristics, whereas an enhancement in radiance was observed (**Fig. 3c**). After encapsulation, the maximum radiance increased from 44.8 W m^{-2} sr^{-1} to 78.7 W m^{-2}

sr^{-1}, accompanied by a 3 nm redshift of the main peak and a 7 nm broadening of the FWHM **(Supplementary Fig. 9a, b).**

Modifications to the revised manuscript in lines 331–334 of the Results section.

Similar trend was observed in devices without encapsulation, indicating that the low level of roll-off, as shown in **Supplementary Figure 9c**. The maximum power density, calculated from the angular distribution of each device, increased from 19 mW cm^{-2} to 33 mW cm^{-2} **(Fig. 3f)**.



Supplementary Fig. 9| Batch-to-batch performance metrics of the NIR OLEDs. a, Current-density–voltage–radiance characteristics. **b,** EL spectra of individual devices driven at a same voltage. **c,** External quantum efficiency as a function of current density. For **a–c**, all devices (n = 10) were measured under identical conditions across batches. (closed symbol: w/ encap, open symbol: w/o encap)

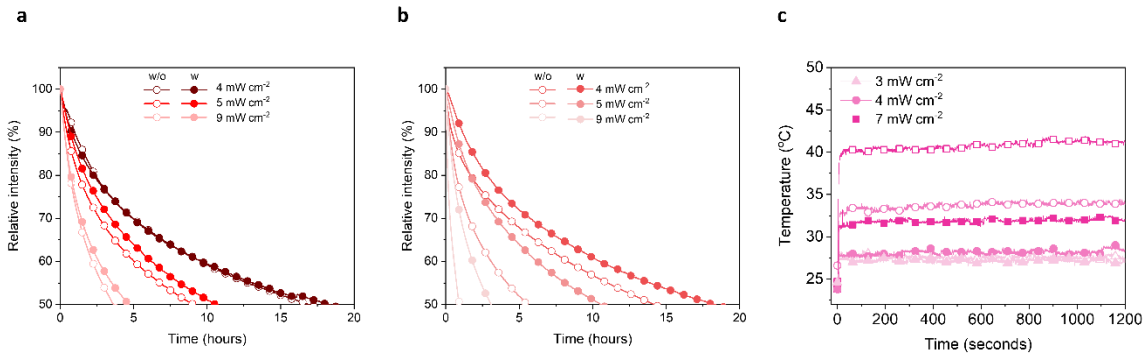
<u>Reviewer's comment 13)</u> Given that EQE roll-off is a critical issue in NIR OLEDs due to triplet-triplet annihilation and thermal quenching, what is the trade-off between brightness and stability? Have you characterized thermal degradation and emission roll-off in that regime?

<u>RESPONSE</u>

We appreciate the reviewer's interest in our study. In response, the brightness–stability trade-off was evaluated by measuring operational lifetime under continuous operation across multiple radiant intensities, with explicit quantification of EQE roll-off and thermal degradation.

At power densities of 4, 5, and 9 mW cm^{-2}, EQEs were 11.14%, 11.10%, and 10.83%, and LT_{50} values were 17, 9, and 4 h, respectively. Across 4–9 mW cm^{-2}, the absolute decrease in EQE was approximately 0.31% (see **FigR.14d** and the **Response to your Comment 12**), whereas LT_{50} decreased sharply with increasing radiant intensity. This trend was independent

of substrate type and was not attributable to the textile platform (**FigR.15a, b**).



FigR.15 | Brightness–stability correlation of NIR OLEDs. a, Operational lifetime (LT_{50}) of glass-based NIR OLEDs under continuous operation as a function of radiant intensity. **b,** Operational lifetime of textile-based NIR OLEDs under continuous operation as a function of radiant intensity. **c,** Operating temperature of the textile-based NIR OLED under continuous operation as a function of radiant intensity. closed symbol: w/o heat sink, open symbol: w/ heat sink.

These results show that EQE roll-off reflects the instantaneous efficiency–current relationship, whereas LT_{50} represents cumulative chemical and interfacial degradation under sustained operation at elevated temperature. In fact, measurements showed that when the radiant intensity was increased from 3 to 7 mW cm^{-2}, the OLED surface temperature rose by approximately 10 °C (**FigR.15c**). Consequently, higher radiant intensity required increased driving voltage and current, which elevated device temperature.

Considering the results indicate that while low roll-off remains across the tested operating range for reached to radiant intensity with sufficient to PBM applications, device stability is degraded at higher radiance due to thermal degradation induced by elevated driving conditions.

We acknowledge that the current NIR OLEDs exhibit limited operational stability for long-term PBM applications, which is primarily attributed to the laboratory-synthesized emissive material rather than commercialized product. Nevertheless, our devices demonstrated sufficient optical output for effective PBM irradiation and for validation as wearable prototypes.

We emphasize that the primary aim of this work was to demonstrate the feasibility of a textile-integrated OLED platform for wearable PBM, rather than to optimize material lifetime. We believe that further development of high-stability emissive materials, combined with reductions in driving voltage and current and enhancements in out-coupling efficiency, will

ultimately enable OLEDs to meet the long-term reliability required for continuous PBM operation.

Reviewer's comment 14) In this work, the merit and demerit of the textile-integrated near-infrared OLED system should be discussed when applied to biocompatible platforms for non-invasive wearable phototherapy.

RESPONSE

We thank the reviewer for requesting a balanced appraisal of the textile-integrated NIR OLED in biocompatible, non-invasive wearable phototherapy. In the revised manuscript, a dedicated subsection has been added in the Discussion.

- **Merits**

1. **Spectral control and therapeutic irradiance.** A top-emitting microcavity architecture was engineered to place the main peak within the therapeutic NIR window and to deliver the required irradiance at practical drive conditions. Additionally, the OLED's structure was tailored to the activation requirements of DP cells to treat hair-loss.
2. **Biocompatible device interface on textile.** Parylene-C–based planarization layer was applied to the textile substrate, and the outermost capping and encapsulation layer of the OLED was also formed with parylene-C. The resulting stack is composed of a biocompatible polymer that provides conformal coverage over textile surface morphology. As known as, parylene-C is a one of the biocompatible polymer which was approved by FDA, is widely employed as a coating for biomedical devices.
3. **Coverage and scalp-specific customization.** Leveraging the OLED light source, which provides large-area emission with a microcavity-tuned spectrum, the emitting areas can be engineered to deliver light selectively to clinically relevant scalp zones with low irradiance nonuniformity.
4. **Wearable form factor and daily usability.** A hat-type platform is a one of the user-friendly platform, it could be improved wearability and supports treatment during routine activities.

- **Limitations**

1. **Angular spectral shift intrinsic to microcavities.** As the emission angle increases, the peak wavelength shifts to the blue. DP-cell activation occurs near 730 nm within the NIR band.

Because phototherapy efficacy is wavelength dependent, this angular blue shift can be disadvantageous by reducing spectral overlap with the cell-responsive band.

2. **Operational stability under continuous drive.** Despite small EQE roll-off at the intended irradiance window, lifetime remains a constraint for prolonged continuous use.

3. **Portable power and runtime**. Sufficient energy density is required to drive an OLED array in a fully flexible, battery-driven system (flexible battery, FPCB, and OLED). A trade-off exists between capacity and mechanical compliance. Generally, greater capacity reduces flexibility.

The revised manuscript describes the merits and demerits of the textile-based NIR OLED platform.

Modifications to the revised manuscript in lines 615–635 of the Discussion section.

The textile-integrated NIR OLED system offers advantages as a biocompatible platform for non-invasive phototherapy. The microcavity structure enables precise spectral control within the therapeutic range, effectively matching the activation spectrum of dermal papilla cells. Using parylene-C, which is FDA-approved material, as both a planarization and encapsulation layer for textile-based OLEDs ensures biocompatibility at the skin interface.[22,24] This material selection strategy enables safe, non-invasive wearable phototherapy in close contact with the skin. In addition, textile-based OLEDs, composed entirely of flexible materials including textile substrate and OLED light source, could be close to the scalp surface and provide uniform illumination of targeted regions with minimal irradiance variation. Furthermore, we have demonstrated a prototype in which embedding the device in a hat-type form factor facilitates natural wearability and comfort, allowing users to receive phototherapy during routine daily activities without the need for benchtop instrumentation, showing its potential as a wearable device.

Despite these advances, several constraints for translation remain. Microcavity OLEDs are characterized by view-angle–dependent spectral shifts, which reduce overlap with cellular

action spectra at oblique incidence. Furthermore, portable operation and device flexibility are limited by trade-offs among deliverable energy density, total device thickness, and capacity of the power-supply components required for OLED driving.

Responses to the reviewer 3's comments

Reviewer #3: The authors did solid OLED engineering work, showing how the proposed device optimization leads to better biological response compared to others (not optimized or similar to commercially available products). The methodology is sound, and the work could be of significance in the field of wearable electronics if adjustments to the manuscripts are properly made.

RESPONSE

We thank the reviewer for the thoughtful and constructive feedback. We believe that this guidance has raised the quality of the manuscript. Detailed point by point responses are provided below.

Reviewer's comment 1) The major point I have is about wearability and usability of the presented device in real life scenarios. The general idea of this work presupposes the existence of a supporting circuitry that ideally fits into the hat, and is removable when washing is necessary (Of course, more creative solutions could be implemented to realize portability, this was just an example). In this regard, I failed to find information about the driving scheme used to realize the videos proposed as demonstrations. For this reason, at the present time, there is the need to add data about this aspect to fully comply with the message of portability proposed in the manuscript, and also to show that this device is indeed compatible with the notion of wearable electronic platforms. In other words, the OLED per se is wearable, but the phototherapy (quoting the title that the authors chose) probably still relies on benchtop power supplies. Therefore, I suggest that the authors come up with a circuitry that allows the OLED to be driven in a truly portable fashion, demonstrating that with the application requirements, the power supply (maybe a battery) can be sufficient to drive the OLED for a substantial amount of time (or equivalently, enough therapeutic sessions). This should be documented in the method section and shown in a Figure.

RESPONSE

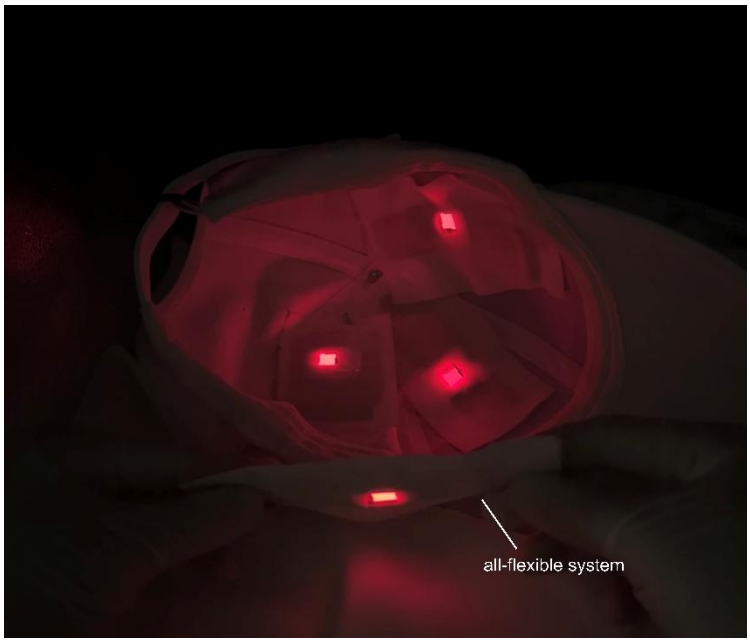
We thank the reviewer for considering real-life scenarios and for noting the lack of information on how the hat-type device is driven. Consistent with your comment, our goal is to demonstrate an integrated phototherapy device based entirely on flexible components, including a textile-based OLED, a battery, and a circuit board. We agree that demonstrating device

portability better substantiates the manuscript's daily-use treatment claim. Accordingly, a fully portable, integrated driving system was demonstrated, and the driving scheme is described in the revised manuscript.

Device portability was demonstrated using a hat-type device based on an all-flexible architecture that integrates a flexible battery for portable operation, a flexible printed-circuit board (FPCB) providing on/off control and battery power delivery, and an OLED.

- **Portable device composed of flexible components**

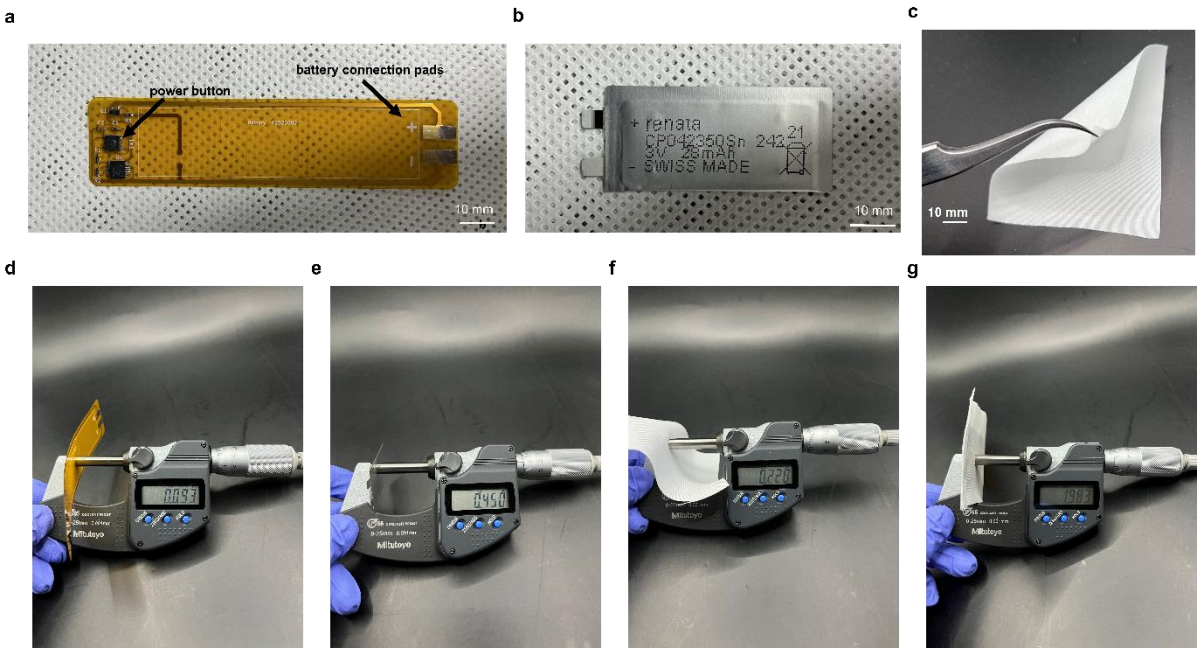
A wireless prototype composed entirely of flexible components was fabricated (**FigR.16**). The system comprised an FPCB, a textile-based single-pixel NIR OLED, and a flexible battery. On/off operation was verified, stable emission was maintained under bending, and the total stack thickness was approximately 2mm. A demonstration video documenting operation without benchtop power supply has been provided **(Supplementary Video 4, 5)**. Switch-driven on–off operation of the OLED stripe array is shown in **Supplementary Video 4**, and stable operation of a wireless cap-type platform integrating multiple OLED stripes during repeated donning and doffing is shown in **Supplementary Video 5.**



FigR.16 | Portable phototherapy hat based on an all-flexible system.

Figure R16 shows the integrated, all-flexible platform used to demonstrate portability. The FPCB provides on/off control and battery connection for portable drive **(FigR.17a)**. The

flexible battery enables wireless operation **(FigR.17b)**. The polyester textile hosts the device stack **(FigR.17c)**. The thicknesses of the FPCB (~90 µm), the flexible battery (~450 µm), and the textile (~230 µm) are reported **(FigR.17d–f)**, and the maximum local thickness of the assembled stack is approximately 2 mm **(FigR.17g)**. Together, these components constitute a fully integrated hat-type module in which power delivery and control are embedded, enabling portable phototherapy without benchtop instrumentation.



FigR.17 | Fully flexible, integrated system. a, FPCB incorporating an on/off power button and battery connection pads for portable driving. **b,** Flexible battery used for wireless operation. **c,** Polyester-based textile substrate. **d–f,** Thickness of the FPCB, flexible battery, and textile, respectively. **g,** Most thick part of the fully flexible integrated stack (around 2 mm).

A wireless hat-type phototherapy prototype intended for portable, daily use was demonstrated. However, we suggest two points for improvement toward a commercial product. First, the present prototype employed 3V battery cells due to lack of flexible battery with sufficient voltage. This voltage was insufficient to drive the NIR OLED at the target operating point that provides sufficient irradiance for phototherapy. Therefore, the batteries were connected in series to realize the demonstration. Development of flexible batteries with adequate voltage and power capacity is required for a commercial product. Second, the overall thickness could be reduced by relocating the FPCB and the battery to alternative regions within the hat to distribute the stack and decrease local thickness.

- **Driving the device for phototherapy**

To achieve the minimum therapeutic emission, the OLEDs were operated at approximately 12 V, as noted in our response to **your Comment 2–6**. For the portable demonstration device, we assembled a flexible power stack using four 3 V thin-film cells (Renata CP042350, 25–28 mAh each) in series to provide ~12 V at the pack level.

For an emission area of 69 mm² with current density around 31.5mA cm^{-2}, the device was driven at approximately I ≈ 7.3 mA to maintain the therapeutic power density. With a series-connected pack capacity of C = 25–28 mAh, the theoretical continuous runtime is:

$$Time_{ideal} = \frac{C}{I} = \frac{25\sim28\ mAh}{7.3mA} = 3.4\sim3.8\ hours$$

Integrated with the FPCB driver and our flexible OLED module, this configuration delivered stable operation at the target current over the 69 mm² aperture and sustained the required radiant output, demonstrating feasibility for portable phototherapy. Given that phototherapy is typically administered in 2–30 minutes, the calculated runtime theoretically confirms that this portable battery configuration provides sufficient operating time.

However, the attainable performance is governed by the battery system and design of circuit board. The choice of rechargeable operation and the addition of a charging function on the FPCB can increase device thickness and reduce mechanical flexibility. Thus, to enable real world use, follow up work is needed to joint design of the FPCB and the battery and the mechanical layout required to preserve flexibility while meeting the electrical and optical targets for phototherapy.

- **Washing compatibility**

To reflect real-world use, both washability and mechanical flexibility are being addressed. For a phototherapy device to be washable, waterproof characteristics are required at the device level and at the interfaces among the battery,[1,2] PCB, and OLED.[3] Washable OLED encapsulation strategies have been reported, and multiple groups are actively investigating washable flexible batteries and washable OLEDs. Additionally, research on waterproofing approaches for PCB and FPCB components is in progress. Although full washability was not implemented in the present prototype, component-level washability is being pursued for each subsystem. Based on these ongoing efforts, we believe that the remaining challenges are expected to be resolved, enabling a washable, integrated device.

References

[R1] He, J., Lu, C., Jiang, H., Han, F., Shi, X., Wu, J., Wang, L., Chen, T., Wang, J., Zhang, Y., Yang, H., Zhang, G., Sun, X., Wang, B., Chen, P., Wang, Y., Xia, Y. & Peng, H. Nature 597, 57–63 (2021).

[R2] Khudiyev, T., Grena, B., Loke, G., Hou, C., Jang, H., Lee, J., Noel, G. H., Alain, J., Joannopoulos, J., Xu, K., Li, J., Fink, Y. & Lee, J. T. Materials Today 52, 80–89 (2022).

[R3] Jeong, E. G., Jeon, Y., Cho, S. H. & Choi, K. C. Energy Environ. Sci. 12, 1878–1889 (2019).

Modifications to the revised manuscript in lines 206–212 of the Results section for providing information of prototype device

Operation of the OLED array on a commercial hat/cap platform, while maintaining the flexibility required for a wearable device, was demonstrated by mounting the array on the textile and interfacing it with a flexible printed circuit board (FPCB) that provided array driving and section-wise switching for scalp-specific operation. The array comprised NIR OLEDs with emission areas of 69 mm^2 and 1,000 mm^2, each wired to an independent FPCB channel to enable individual on/off control of each scalp section.

Modifications to the revised manuscript in lines 221–231 of the Results section.

Furthermore, a wireless phototherapy device composed entirely of flexible components was fabricated to validate portable operation. The system comprised a FPCB for switch-based on/off control and battery-driven OLED operation, the NIR OLED, and a flexible battery (**Supplementary Fig. 3a, b**). The individual component thicknesses were ~90 μm (FPCB), ~230 μm (textile), and ~450 μm (battery), and the maximum local stack thickness within the hat form factor was ~2.0 mm (**Supplementary Fig. 3c–f**). Switch-controlled on/off operation of the textile-based OLED stripe integrating fully flexible components was demonstrated without the use of a benchtop power supply (**Supplementary Video 4**). For a cap-type platform integrating multiple OLED stripes, continuous emission was maintained during donning and doffing (**Supplementary Video 5**).

Modifications to the revised manuscript in lines 635–647 of the Discussion section.

To reach real-world applicability, further technological refinement is required. The development of flexible batteries with sufficient voltage and power capacity is essential for commercial deployment. Reducing overall thickness through redistribution of the FPCB and battery across alternative hat regions would improve user comfort and decrease localized bulk. In addition, practical use demands that washability and mechanical flexibility be achieved simultaneously. Attaining washability requires comprehensive waterproofing at the device level and reliable sealing of interfaces among the battery, FPCB, and OLED. Although full washability has not yet been implemented in the current prototype, component-level studies on waterproof OLED encapsulation,[38] flexible batteries,[39,40] and circuit boards are ongoing. These efforts are expected to fabricate a fully washable and stable system capable of sustained operation in daily use, thereby advancing the textile-integrated NIR OLED platform toward practical, commercially viable wearable phototherapy.

Modifications to the revised manuscript in lines 684–701 of the Method section.

Hat-type prototype

To demonstrate operation of the OLED array on a commercial hat/cap platform, the array was mounted on the textile and interfaced to a flexible printed circuit board (FPCB) that provided array driving and section-wise switching for scalp-specific operation. The array comprised OLED emitters with emission areas of 69 mm^2 and 1,000 mm^2, each wired to an independent FPCB channel for individual on/off control. For array-level characterization, the source was operated in constant-current mode using a benchtop sourcemeter (Keithley 2636B). The operation is shown in **Supplementary Videos 1–3**.

A wireless prototype was assembled to evaluate portability. The architecture integrated a flexible battery for portable operation, a flexible printed circuit board providing on/off control,

battery power delivery, and OLED interconnection, and the NIR OLED. A 3V flexible Renata thin-film battery (CP042350) was employed, and 4 cells were connected in series to achieve the required minimum level of light intensity for phototherapy. All components were integrated on the polyester-based textile to form a single portable module, and operation was performed from the flexible battery without benchtop supply **(Supplementary Videos 4, 5)**.

Reviewer's comment 2) I have some minor comments referring to the different sections of the manuscripts.

RESPONSE

We greatly appreciate the opportunity to improve the manuscript based on your detailed comments.

Reviewer's comment 2-1) ROW 102: "Additionally, most NIR OLEDs have been designed a bottom-emitting architecture" probably contains an error.

RESPONSE

Most NIR OLEDs reported to date have been implemented as bottom-emitting devices, owing to a prevailing focus on the synthesis of novel NIR emitters rather than on application-oriented device design. As noted by the reviewer, the original sentence could lead to misunderstanding; therefore, the wording has been revised to clarify our intent.

Modifications to the revised manuscript in lines 103–106 of the Introduction section.

Most NIR OLEDs reported to date adopt a bottom-emitting structure, in which light exits through the substrate. An optical characteristic of the NIR OLEDs are highly dependent on substrate transmittance, which inherently restricts the range of applicable substrate materials.[13,20]

Reviewer's comment 2-2) ROWS 115-116: Typically, bottom emitting OLEDs provide different advantages over top-emitting ones. While it is clear that bottom emitting devices based on ITO are susceptible to mechanical damage under certain stress, the author here exclude the whole category of bottom-emitting OLEDs without addressing the general motivation. Could they elaborate more on this design choice?

RESPONSE

To address the reviewer's question regarding our structural choices, the reason is summarized below.

- **Reason for employing a top-emitting architecture**

1. The textile platform exhibits low transmittance in the near‑infrared (NIR) range (≈20%). Thus, emission through the substrate is inefficient. A top-emitting

configuration was therefore selected to extract light away from the textile and to ensure efficient optical delivery to the target tissue.

- **Reason for employing a silver electrode instead of ITO**

1. Mechanical compliance for wearability: Ag-based thin electrodes provide lower sheet resistance at comparable or lower thickness than ITO and remain operational at higher bending strains, which supports the flexibility required for wearable electronics.
2. Spectral control for PBM: In a cavity-tuned, top-emitting stack, the Ag semi-transparent electrode (together with the reflective bottom mirror and capping layers) enables precise control of the optical resonance. This allows tuning of the peak wavelength and linewidth without changing the emitter, which is critical for PBM where efficacy is strongly wavelength dependent.

Modifications to the revised manuscript in lines 116–119 of the Introduction section.

To improve the phototherapeutic efficacy of wearable, textile-integrated NIR OLEDs for hair-loss treatment, a microcavity structure was used. This architecture enables spectral tuning without changing the emitter material, as PBM outcomes are strongly wavelength dependent.

Reviewer's comment 2-3) ROW 128: Why are the authors using this specific tensile strain (2.1%)? What are the ranges of expected strains during use and during washing of the "hat"? It is suspected that this object will face grater deformations for the intended wearable application. What would be the number of bending tests that the OLED would tolerate for a strain in the range conform to the application needs?

RESPONSE

Thank you for the comment. Responses to each question are provided below.

- **Reason for choosing the specific strain (2.1%)**

First of all, a strain of 2.1% corresponds to a bending radius of 2 mm for the textile platform. For planar substrates, the bending strain of OLEDs is approximated by t/2R; however, because the textile substrate consists of a woven warp and weft architecture, this planar approximation is not applicable. Therefore, the bending strain in the textile platform was determined by finite element analysis.[1] The analysis indicated that the highest strain that can be quantified reliably

occurs at 2.1% when the bending radius is 2 mm. Beyond this point, an accurate definition of strain becomes ambiguous. Accordingly, a nominal strain of 2.1% was applied to the textile OLED for the bending tests.

Additionally, previous studies have reported that textile-based red OLEDs maintained stable performance even after 1,000 bending cycles at a bending radius of 1.25 mm.[2] Although the exact strain applied to the textile cannot be precisely defined, this observation demonstrates that the flexibility of textile OLEDs can be preserved even under more severe bending conditions.

- **Strain in real-world use**

The typical curvature radius of an adult head is approximately 90 mm.[3] This value indicates a much gentler curvature than R = 2 mm, under which the textile-based OLED remained stable for up to 10,000 bending cycles.

- **Considerations for hat washing**

Because the hat is flexible, machine washing can fold the device (effective R ≈ 0), imposing large strain under which the OLED may be damaged. This issue could be addressed by mechanically optimizing the device architecture so that the neutral axis coincides with the OLED, thereby minimizing bending-induced strain. As a temporary expedient, hand washing rather than machine washing is recommended to mitigate strain and maintain the mechanical stability of the textile OLED device.

To clarify the textile bending condition, the bending radius value was included in Introduction section.

Modifications to the revised manuscript in lines 128–131 of the Introduction section.

The flexibility of the textile-based top-emitting OLEDs were validated through repeated bending tests, confirming stable radiance output and mechanical robustness without delamination even after 10,000 bending cycles at a bending radius of 2 mm, corresponding to 2.1% tensile strain.

References

[R1] Lee, J., Gu, C. Y., Chang, J., Cho, E. H., Kim, T. S., & Choi, K. C. *npj Flexible Electronics*, 8, 73 (2024).

[R2] Cho, H. E., Kim, M. J., Chang, J., An, J., Na, Y., Choi, S., Jeong, S. Y., & Choi, K. C. *npj flexible electronics*, 9, 36 (2025).

[R3] Borghi, A., Heutinck, P., Rodriguez-Florez, N., Koudstaal, M., Ruggiero, F., Ajami, S., Schievano, S., Jeelani, N.U.O. & Dunaway, D. *The Cleft Palate Craniofacial Journal*, 60, 1591-1599 (2023).

<u>Reviewer's comment 2-4)</u> ROW 183: I think the authors should reference figures 3 and 5 here.

<u>RESPONSE</u>

Thank you for your consideration. To improve reader comprehension, Fig. 3 has been cited earlier in the encapsulation content.

Modifications to the revised manuscript in lines 188–191 of the Results section.

This hybrid encapsulation, consisting of the upper TFE and outermost parylene-C layer, not only provides needed mechanical protection but also enhances light extraction efficiency (**Fig. 3**). Details on the light-extraction enhancement by the hybrid capping are provided in a subsequent section.

<u>Reviewer's comment 2-5)</u> ROWS 246—248: It is useful for the reader to directly access the information about the ETL and HTL thickness from this line. Could the authors explicitly state the thicknesses in the non-optimized VS. optimized case and provide an explanation for their claim on the better carrier transport in the optimized configuration?
<u>RESPONSE</u>

Thank you for the helpful suggestion. The ETL and HTL thicknesses for the non-optimized and optimized devices have been included in the revised manuscript.

To keep the optical cavity length identical across cases, the same increment was applied. In the HTL-tuned device, increasing the NPB layer (HTL) by 37 nm aligned the main EL peak at 730 nm. Based on this result, to maintain the cavity length for each case, the ETL-tuned device was fabricated by increasing the TPBi layer (ETL) by 37 nm. As detailed in our response to **Reviewer 2, Comment 9**, additional validations were performed at matched radiance for both the HTL-tuned and ETL-tuned OLEDs, including operational lifetime and angle-resolved emission intensity. The advantages associated with the recombination zone position in each configuration, including benefits in light extraction and carrier transport, were included in the revised manuscript.

Modifications to the revised manuscript in lines 259–265 of the Results section.

To compare the two tuning strategies, the optical cavity length was maintained constant by applying an identical thickness increment to either the HTL or ETL. In the HTL-tuned OLED, the NPB layer was increased by 37 nm relative to the conventional recipe, which adjusted the optical path and positioned the main EL peak at 730 nm. Using this optimized condition as a reference, the ETL-tuned OLED was fabricated by extending the TPBi layer by the same 37 nm, thereby preserving an equivalent cavity length across both configurations.

Modifications to the revised manuscript in lines 280–285 of the Results section.

Because hole transport in NPB exceeds electron transport in TPBi, adjustment of the NPB thickness, in part owing to the carrier mobility imbalance,[27] positioned the recombination zone more effectively within the emissive layer, to reduce the proportion of non-radiative interfacial

exciplex. In fact, the HTL-tuned OLED exhibited slightly improved operational lifetime compared with the ETL-tuned device **(Supplementary Fig. 4b)**.

Reviewer's comment 2-6) ROW 307: What are the requirements in terms of optical power density (or equivalently energy density) that are required to exhert relevant beneficial effects with this type of therapy? This information is difficult to retrieve without accessing to reference 7. I think it would be of service to explicitly mention this in the text. It is also important to state at what voltages and currents the OLEDs presented in this work reach this range.

RESPONSE

Thank you for the comments. The revised manuscript was included the minimum specific intensity required for phototherapy. In addition, the input power of the textile device required to reach sufficient light intensity for a phototherapeutic effect has been specified.

Modifications to the revised manuscript in lines 349–352 of the Results section.

In addition, device stability was maintained without any detectable leakage paths, and the emitted light intensity exceed 10 W m^{-2} sr^{-1} at approximately 12 V and a current density of 31.5 mA cm-2 for the textile device, the minimum level required for phototherapy **(Supplementary Fig. 10b)**.[7]

Reviewer's comment 2-7) ROW 320: See the comment related to the choice of a 2.1% strain.

RESPONSE

Thank you for the comment. The description of the strain defined by finite element analysis of the textile's woven warp and weft architecture has been added to the revised manuscript.

Modifications to the revised manuscript in lines 356–360 of the Results section.

Flexibility of the textile-based device was assessed by cyclic bending at a radius of 2 mm, corresponding to an applied tensile strain of 2.1%. Finite element analysis indicated that, for the textile platform with a woven warp and weft architecture, this condition represented the maximum point at which the applied strain could be defined.[22]

<u>Reviewer's comment 2-8)</u> ROW 341: I think the content of ROWS 355-361 should be moved here for better readability.

<u>RESPONSE</u>

Thank you for the helpful suggestion on readability. We agree and have revised the manuscript accordingly to enhance clarity and flow.

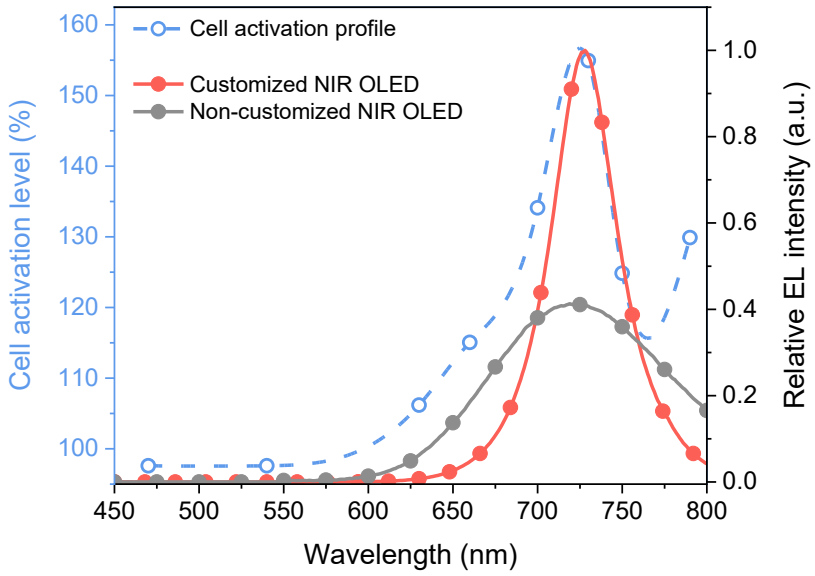
Modifications to the revised manuscript in lines 378–384 of the Results section.

Regardless of applied current density, their temperature levelled shortly after initiation. The devices reached 28.0 °C at 3 mW cm^{-2}, 34.0 °C at 4 mW cm^{-2}, and 41.0 °C at 7 mW cm^{-2}, respectively. The polyester-based textile platform used in this study possesses a relatively low thermal conductivity (0.3–0.4 W/m·K), significantly lower than that of glass (~1 W/m·K). Such thermal accumulation leads to heat retention in the active layer during prolonged operation, thereby accelerating device degradation. Reducing heat accumulation and suppress OLED degradation caused by heat, a heat sink tape was attached to the textile devices.

<u>Reviewer's comment 2-9)</u> ROW 495: It would be appropriate to show a plot with the superposition of hDPC activation spectrum (or peak if not available) and the different OLEDs EL spectra. Most probably the authors can add the hDPC missing information directly into figure 2E.

<u>RESPONSE</u>

We appreciate the reviewer's recommendation. We agree that plotting the overlap between the OLED EL spectra and the cell activation spectrum significantly improves reader comprehension and supports our main argument. Accordingly, the activation spectrum was incorporated into modified **Figure 5d**, comparing the customized and non-customized OLEDs. The revised manuscript has been updated to reflect this change. Thank you for the valuable suggestion.



Modified Fig. 5d | Overlap between the human dermal papilla cell action spectrum for proliferation[13] and the EL spectra of the cavity NIR OLED and non-cavity NIR OLED under same radiance

Voluntary modification

Beyond the point-by-point responses for reviewers, several voluntary revisions were made to enhance clarity and reproducibility of the work.

1. **Edits for improving readability.** The manuscript text was improved by providing detailed description.
2. **Figures improved.** We refined and, where helpful, expanded the main figures and supplementary materials to present key results more clearly.
3. **Methods expanded.** We added procedural details to support replication.
4. **Source data provided.** We supply complete source data files in this study.

We believe that these updates could be assisted readers and reviewers by improving readability and enabling precise reproduction of the experiments and analyses.

Again, we would like to express our appreciation for the reviewers' thoughtful suggestions. We have been able to revise and improve the paper because of the reviewers' valuable feedback. We look forward to your positive response.

Thank you very much for your time and attention.
Sincerely yours,

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Responses to the reviewer 1's comments

Reviewer #1: The authors have substantially revised the manuscript "Wearable textile-based phototherapy with customized near-infrared OLEDs for superior hair loss treatment" in response to the first-round reviews. In particular, they added (1) pilot in vivo experiments using a mouse model together with ex vivo skin-penetration measurements, (2) quantitative analysis of power density and on-cell irradiance supported by Monte Carlo simulations in a layered skin model, and (3) a clearer positioning of their textile NIR OLED platform relative to commercial PBM devices and previously reported cage-OLED / micro-LED systems. I thank the authors for their detailed and constructive revision. The additions to the manuscript and response letter clearly show substantial effort. The new data and analysis improve the rigour of the optical characterization and strengthen the positioning of the textile-integrated NIR OLED platform. My major concerns about optical dose characterization and benchmarking (previous Comments 2 and 3) are now largely addressed. The remaining weakness is that in vivo validation of therapeutic efficacy is still preliminary: the new data mainly document light delivery through murine skin and ongoing animal studies, but do not yet demonstrate hair-growth outcomes or dose–response relationships. The authors have, however, clarified these limitations and softened their claims. Given the device-centric nature of the work and the strengthened quantitative analysis of light delivery, I believe the manuscript is now much closer to the bar of Nature Communications. I would be comfortable with publication after minor revision, mainly to ensure that the limited status of the in vivo data is clearly conveyed in the main text.

RESPONSE

We sincerely appreciate the reviewer's insightful comments and the interest to our work. Our point-by-point responses are provided below.

Reviewer's comment 1) Regarding previous comments on the scope of biological validation / in vivo relevance: These additions partially address my original concern. In particular: (1) The skin-penetration measurements are useful and directly relevant to the question of whether sufficient NIR power can reach the follicular region in a realistic setting. (2) The explicit acknowledgment that full in vivo hair-growth validation is ongoing and non-trivial makes the biological scope of the current work more honest and transparent. However, the in vivo component remains exploratory rather than systematic. The material presented in Fig. R1 mainly documents the experimental setup rather than quantitative biological outcomes (e.g., hair-density maps, histology, or longitudinal regrowth curves). I understand that performing a comprehensive preclinical efficacy study may be beyond the scope of this device-focused paper; in that case, the main text should clearly avoid overstating therapeutic claims. Therefore, in the revised manuscript, please ensure that statements about "superior hair-loss treatment" or "therapeutic efficacy" are toned down and framed as potential or anticipated benefits supported by cellular assays and realistic light-delivery analysis, rather than as fully demonstrated in vivo outcomes. It would also be helpful to summarize the key quantitative numbers from the skin-penetration experiment (relative radiance with

shaved vs. depilated skin) in the main text or a main-figure panel, not just in the response.

RESPONSE

We appreciate the reviewer's comments on the scope of biological validation and the need to tone down therapeutic claims. To avoid over-interpretation of the present experimental results and to more clearly delineate the scope and significance of this work, we have revised the wording throughout the manuscript. In particular, statements regarding the effects of the NIR OLED system are now framed as potential or anticipated benefits supported by in vitro cellular assays and realistic light-delivery analysis, rather than as fully demonstrated in vivo therapeutic outcomes.

Modifications to the revised manuscript in lines 16–32 of the Abstract section

To provide a non-pharmacological alternative, a wearable textile-integrated near-infrared (NIR) organic light-emitting diode (OLED) platform was developed with emission closely aligned with the action spectrum of human dermal papilla cells (hDPCs). By employing a top-emitting microcavity structure, we tuned the emission peak of the NIR OLEDs (around 730–740 nm) to align with the hDPC activation spectrum, thereby enhancing photon delivery to the follicle niche and enabling irradiation at wavelengths that promote hDPC photoactivation. This non-invasive, skin-conformable textile-based device exhibits mechanical resilience to repeated bending at a radius of 2 mm, low heat generation to prevent skin burns, and waterproof performance under water immersion. In vitro, NIR irradiation from the customized microcavity-tuned OLED device significantly reduced senescence-associated β-galactosidase activity by 91.6% and increased hDPC migration, with greater effects than those observed for red light and broad full-width at half-maximum (FWHM) NIR irradiation groups. These findings suggest that microcavity-tuned textile-based NIR OLEDs can serve as scalable, biocompatible platforms for non-invasive wearable phototherapy aimed at hair-follicle modulation and future hair-loss management.

Modifications to the revised manuscript in lines 399–402 of the Results section

Since human hair follicles are typically located approximately 3 mm beneath the skin surface, achieving light transmission to this depth is critical for effective light delivery to dermal papilla cells within the follicle niche.

Modifications to the revised manuscript in lines 638–646 of the Discussion section

In addition, hair-loss pathology involves multiscale interactions that extend beyond hDPC responses, including crosstalk with epithelial stem cells, immune system, the vasculature and systemic endocrine signals. Therefore, the results obtained from our *in vitro* tests should be interpreted as evidence of photobiological modulation at the cellular level rather than as direct proof of hair-loss treatment. To establish whether wavelength-optimized textile-integrated NIR OLEDs can ultimately provide clinically meaningful benefits, future studies will need to include controlled *in vivo* models and, eventually, clinical trials to evaluate changes in hair density, hair-shaft thickness and hair length.

<u>Reviewer's comment 2)</u> Regarding benchmarking vs FDA-cleared clinical systems: The revisions substantially strengthen the manuscript. The combination of measured irradiance, modelled dose in tissue, and angular emission data now provides a quantitative and mechanistic basis for discussing light delivery, rather than relying on qualitative statements alone. The benchmarking against commercial devices is necessarily limited by the sparse publicly available specifications, but the discussion is reasonable and helps to contextualize the work. Moreover, I suggest ensuring that typical ranges of fluence and irradiance used in clinical PBM protocols are cited and that your operating regime is clearly positioned within those ranges. This will help readers outside the PBM community interpret the numbers. Consider summarizing the key benchmarking parameters (e.g., wavelength, approximate irradiance at the scalp, form factor) in a compact comparison table in the main text, even if the underlying details remain in the Supplementary materials.

<u>RESPONSE</u>

We agree with the reviewer that clearly positioning our operating regime with respect to typical fluence and irradiance ranges used in clinical PBM protocols is important. We have compiled values from relevant literature and added a compact comparison table to the manuscript that summarizes key benchmarking parameters (such as wavelength, form factor, and light source) for our textile device and representative helmet-type devices.

Modifications to the revised manuscript in lines 57–64 of the Introduction section

A notable class of commercial PBM systems for hair-loss treatment adopts helmet- or hairband-type configurations incorporating arrays of LEDs and lasers.[9–11] This device is characterized by a mechanically robust helmet-type design that can be securely fixed to the head. However, the platforms are restricted to use in indoor home environments rather than during daily outdoor activities, and the reliance on numerous point-like LED and laser emitters, each illuminating only a small area, necessitates large emitter counts to cover the scalp, which can increase the overall device weight.

Modifications to the revised manuscript in lines 234–242 of the Results section

Clinically validated light-therapy systems for hair loss, such as helmet- and headband-type devices, have demonstrated therapeutic effects but rely on rigid platforms that are primarily suited for indoor use. In this study, the textile-based NIR OLED was implemented in

a hat-type platform to propose a phototherapy device design that can be used in both indoor and outdoor settings. Compared with conventional rigid systems, this textile-integrated design offers mechanical flexibility and conformal contact with the scalp and employs an OLED-based NIR area source rather than point-like emitters such as red LEDs or lasers, enabling more uniform illumination over the treatment region **(Table 1)**.

Characteristics of phototherapy devices for hair-loss treatment				
Characteristics	Devices			
	Ref. 9	Ref. 10	Ref. 11	This work
Light source	Laser	LED + Laser	LED + Laser	OLED
Wavelength	Red (655 ± 33 nm)	Red (630 ± 20, 655 ± 5 and 660 ± 7 nm)	Red (630, 650 and 660 nm)	NIR (730 ± 10 nm)
Power density	-	3.04 mW cm^{-2}	92.15 mW cm^{-2}	3 mW cm^{-2}
Platform	Hairband	Helmet	Helmet	Hat
Flexibility	Rigid	Rigid	Rigid	Flexible
Usage environment	Home use (indoor)	Home use (indoor)	Home use (indoor)	Unrestricted (indoor and outdoor)
Study type	Clinical	Clinical	Clinical	*In vitro*

Table 1. Key characteristics of phototherapy platforms for hair-loss treatment

Reviewer's comment 3) When discussing the in vivo mouse work, I suggest avoiding explanations that could be interpreted as complete therapeutic validation; instead, emphasize that these are pilot studies demonstrating the feasibility of light delivery and setup for future efficacy experiments.

RESPONSE

We appreciate this constructive suggestion and agree that the in vivo mouse experiments should not be interpreted as complete therapeutic validation. In the revised manuscript, the in vivo data are explicitly described as pilot studies demonstrating the feasibility of light delivery and experimental setup for future efficacy experiments, and we will keep this important distinction in mind when designing and reporting future work.

Reviewer's comment 4) I suggest some careful edits to remove any remaining instances of over-strong claims, such as "superior hair loss treatment" in contexts where in vivo hair regrowth is not yet shown, which would improve the overall balance of the manuscript.

RESPONSE

We appreciate the reviewer's suggestion to remove remaining instances of over-strong claims and fully agree that such wording could be misleading in the absence of in vivo hair-regrowth data. Accordingly, the wording has been carefully revised throughout the manuscript to avoid implying demonstrated therapeutic superiority. In particular, the expression "superior hair loss treatment" has been removed from the title and main text, and all descriptions of therapeutic effects have been reframed as potential or anticipated benefits supported by in vitro assays and realistic light-delivery analysis.

Modified Title: Wearable textile-based phototherapy with customized near-infrared OLEDs toward hair-loss treatment

Responses to the reviewer 2's comments

Reviewer #2: **The authors well-replied and address the concerned sections. Therefore, I suggested that the current revised manuscript can be accepted by Nature Communications.**

RESPONSE

We sincerely appreciate the reviewer's positive assessment and recommendation for acceptance. We believe that the incorporation and refinement of the Monte Carlo light-transport simulations, as suggested, has substantially strengthened the mechanistic foundation of this study and its relevance under realistic conditions. This revision process has been a valuable experience for us.

Responses to the reviewer 3's comments

Reviewer #3: **Amazing work.**

RESPONSE

We sincerely appreciate the reviewer's positive comment. Developing the NIR OLED devices and textile-based prototypes has been a highly rewarding experience for us, and we are grateful that the reviewer found value in this work.