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Future horizons in cancer treatment: Advancement in photodynamic therapy using OLED technology

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Abstract
Photodynamic Therapy (PDT) is a minimally invasive technique increasingly used in the treatment of cancer. It involves three essential components: a light-sensitive compound known as a photosensitizer, a specific wavelength of light, and molecular oxygen naturally present in the body. When light is applied to the target area, it activates the photosensitizer, leading to the formation of Reactive Oxygen Species (ROS). These reactive molecules cause localized damage to cancerous cells while leaving healthy tissues mostly unaffected. This targeted mechanism allows PDT to offer a safer and more selective alternative to conventional cancer therapies such as chemotherapy and radiation.
However, the effectiveness of conventional PDT is limited by certain factors. Most notably, the light used in traditional PDT systems cannot penetrate deeply into tissue, making it difficult to treat tumours located beneath the skin or within internal organs. Additionally, some photosensitizers used today lack high selectivity or fail to produce strong therapeutic effects, which may reduce the success of the treatment. Recent advancements in organic Light-Emitting Diode (OLED) technology present new opportunities to overcome these limitations. OLEDs are thin, flexible, and capable of emitting consistent light, making them suitable for medical applications. Their tenable properties allow for the development of devices that emit light in the near-infrared (NIR) range, which is known for deeper tissue penetration compared to visible light. This characteristic can help extend the reach of PDT to tumours located in previously inaccessible areas. Furthermore, OLED-based devices can be integrated with smart delivery systems using nanotechnology to improve the accuracy and performance of photosensitizers. These systems enhance the concentration of therapeutic agents in tumour tissue while reducing side effects. Wearable OLED light patches can also adapt to body contours, providing even and continuous illumination during treatment. In addition, the incorporation of advanced light control systems, such as those enhanced with quantum dots, can result in more precise and effective light delivery. In summary, combining OLED technology with advanced photosensitizers and delivery platforms holds significant potential for improving the performance of photodynamic therapy. These innovations aim to enhance treatment depth, efficiency, and safety, ultimately making PDT a more reliable and personalized option for cancer care.

Keywords: Photodynamic therapy, OLED, cancer treatment, nanomedicine, wearable devices, NIR light, personalized therapy, smart photosensitizers, AI-guided treatment

1. Introductions
Cancer continues to be a leading cause of death globally, accounting for significant morbidity despite ongoing progress in clinical management. Conventional treatments such as surgery, chemotherapy, and radiation therapy remain the standard approaches; however, they are often associated with substantial limitations, including non-specific toxicity, damage to healthy tissue, immune suppression, and extended recovery periods. These challenges have led to increasing interest in alternative therapeutic modalities that are more targeted, minimally invasive, and better tolerated by patients.
Among emerging techniques, Photodynamic Therapy (PDT) has shown promising clinical potential. PDT involves the administration of a photosensitizing agent, which preferentially accumulates in malignant tissues. When exposed to a specific wavelength of light in the presence of oxygen, the photosensitizer becomes activated, resulting in the generation of Reactive Oxygen Species (ROS). These ROS induce oxidative damage, leading to selective destruction of cancerous cells while sparing most healthy tissue. The non-invasive nature of PDT, along with its compatibility with repeated treatments and adjunctive use alongside chemotherapy or immunotherapy, highlights its therapeutic value. Despite these benefits, PDT faces significant barriers to broader clinical implementation. Chief among them is the

limited tissue penetration of conventional light sources, such as lasers and Light-Emitting Diodes (LEDs), which restricts the treatment primarily to surface-level or easily accessible tumours. In addition, some photosensitizers suffer from inadequate tumour selectivity or poor photochemical reactivity, thereby limiting therapeutic efficacy. To address these shortcomings, researchers have increasingly turned to Organic Light-Emitting Diodes (OLEDs) as innovative light sources for PDT. OLEDs are inherently lightweight, flexible, energy-efficient, and capable of emitting homogenous light over irregular surfaces. These properties make them highly suitable for integration into wearable or implantable medical platforms, potentially enabling localized and real-time phototherapy for deep-seated tumours.

This paper investigates the synergistic potential of OLED-integrated PDT systems in enhancing cancer treatment outcomes. Key technological innovations explored include:

1.	NIR OLEDs for deeper tissue reach
2.	Nanotechnology-based smart photosensitizers that activate more precisely
3.	Wearable OLED devices that move with the body
4.	Artificial intelligence (AI) to design and monitor personalized treatments
5.	Quantum dots to increase the brightness and efficiency of light delivery.

1.1 Near-infrared OLEDs for deeper tumour targeting

Visible light, typically emitted by conventional OLEDs, is limited in clinical phototherapy due to its shallow tissue penetration caused by absorption and scattering in biological media. Near-infrared (NIR) OLEDs, functioning within the 800–1000 nm wavelength range, overcome this limitation by enabling significantly deeper photon penetration into tissues. This makes them particularly effective for activating photosensitizers in tumours located beneath the skin or within internal organs. Recent developments in NIR emitters, particularly iridium-based phosphorescent complexes, have significantly enhanced the operational efficiency and emission stability of OLED systems, supporting their application in non-invasive cancer treatments.

1.2 Nanocarrier-based photosensitizers for tumour-specific activation

Nanotechnology plays a transformative role in photodynamic therapy by enabling the encapsulation of photosensitizers within nanocarriers tailored for selective tumour targeting. These nano systems are designed to respond to unique features of the tumour microenvironment such as acidic pH, elevated enzymatic activity, or hyperthermic conditions. Upon encountering these stimuli, the nanocarriers disintegrate or open, releasing the photosensitizer precisely at the tumour site. This mechanism minimizes off-target effects, protects healthy tissues, and enhances the overall selectivity and therapeutic impact of the treatment.

1.3 Wearable OLED devices for flexible light delivery

Fixed light sources in traditional PDT platforms often limit treatment to static environments, which can be restrictive for patients. In contrast, wearable OLED systems, constructed from lightweight, flexible materials, are designed to conform to various anatomical surfaces and move with the body. These devices allow continuous light exposure even during normal activity, supporting therapeutic delivery on anatomically complex or mobile regions such as facial contours or joints. The integration of such wearable platforms enhances patient comfort and enables extended therapy sessions without confinement.

1.4 Artificial intelligence for personalized photodynamic treatment

Artificial intelligence is revolutionizing photodynamic therapy by enabling highly individualized treatment strategies. By analysing patient-specific data including tumour morphology, photosensitizer pharmacokinetics, and real-time imaging AI algorithms can determine the optimal light dose, exposure duration, and timing. During treatment, AI systems can monitor therapeutic response dynamically and adjust parameters accordingly. This real-time adaptability ensures improved treatment precision and maximizes therapeutic outcomes, aligning with the goals of precision medicine.

1.5 Quantum dot integration for enhanced OLED emission

Quantum dots are semiconductor nanocrystals that emit sharp, tuneable light when electrically excited. When incorporated into OLEDs, they produce spectrally precise and high-intensity light, which is ideal for activating photosensitizers with specific absorption profiles. This precision minimizes unnecessary tissue exposure and increases the overall energy efficiency of light delivery. Additionally, quantum dot–based OLEDs exhibit high photostability and durability, making them suitable for sustained phototherapeutic applications in varied clinical settings.

2. Background

Photodynamic Therapy (PDT) is a targeted, minimally invasive cancer treatment that operates through a photochemical process involving three key components: a photosensitizer, a specific wavelength of light, and molecular oxygen. Upon activation by light, the photosensitizer generates reactive oxygen species (ROS), particularly singlet oxygen (O_2), which lead to cancer cell death through apoptosis or necrosis.

However, traditional light sources used in PDT such as lasers and inorganic LEDs present several limitations. These systems are typically rigid, require high energy input, and emit light in the visible spectrum (400–700 nm), which has limited penetration depth in biological tissues, often less than 1cm. As a result, treatment is largely restricted to superficial tumours. Additionally, many conventional photosensitizers, including porphyrins and chlorins, suffer from poor tumour specificity and low quantum yields, limiting their clinical effectiveness.

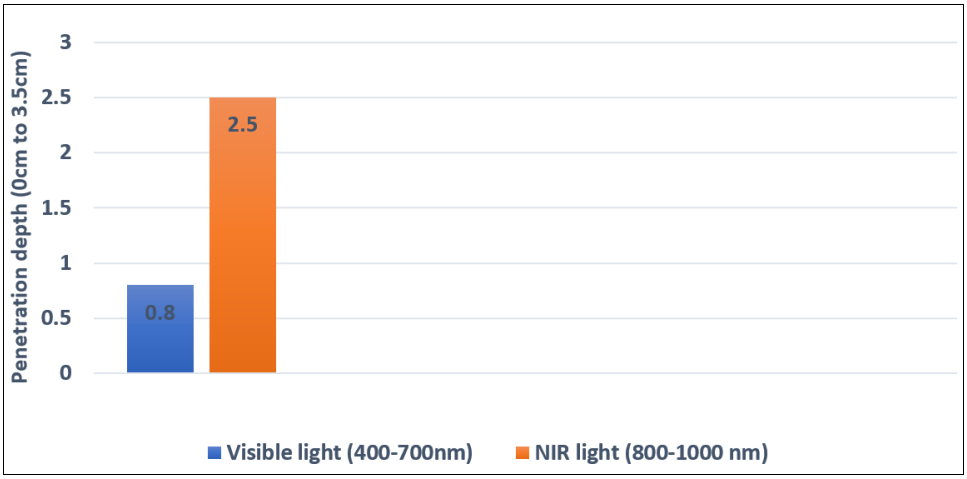
Organic Light-Emitting Diodes (OLEDs) have emerged as a compelling alternative due to their lightweight structure, mechanical flexibility, and tuneable emission properties. Notably, OLEDs can be engineered to emit light in the Near-Infrared (NIR) range (700–1000 nm), which allows for deeper tissue penetration and improved activation of photosensitizers in subcutaneous or deep-seated tumours. Recent studies have explored the integration of OLEDs into PDT systems, aiming to improve treatment precision,

enhance therapeutic efficiency, and increase patient comfort through wearable or implantable light delivery platforms.

3. Advancement in OLED-based PDT

3.1 Near-Infrared (NIR) OLEDs for deeper tissue penetration

Visible light used in traditional PDT is absorbed or scattered by biological tissues, limiting its reach to superficial tumours. NIR OLEDs, emitting in the 800-1000nm range, exploit the biological transparency window, where absorption by water, hemoglobin, and melanin is minimal, allowing penetration depths of 2cm to 3cm. This enables treatment of deep-seated tumours in organs like the liver or pancreas.



Advancement in NIR-emitting materials, such as iridium-based phosphor fluorescent complexes and thermally activated delayed fluorescence (TADF) emitters, have external quantum efficiencies (EQEs) exceeding 15%, ensuring sufficient light intensity for photosensitizer activation. These materials enhance OLD stability and biocompatibility, critical for medical applications.

3.1.1 Next-generation NIR OLEDs

Near-Infrared OLEDs (800-100nm) reduce light scattering and absorption, enabling deeper tissue penetration [5]. Advances in phosphorescent materials, such as iridium complexes, improve emission efficiency. For example, an NIR OLED with a quantum efficiency of 20% can deliver sufficient light to activate PSs at depths of 15-20mm suitable for pancreatic or brain cancers.

Example 1: Calculate light penetration depth

The penetration depth δ of light in tissue is given by:

$$\delta = \frac{1}{\sqrt{3\mu_a(\mu_a + \mu_s')}}$$

Where:

μ_a = Absorption cofficient (in cm^{-1})
μ_s' = Reduce scattering cofficient (in cm^{-1})

Case 1: NIR light at 850nm

Given
$\mu^a = 0.1 cm^{-1}$
$\mu_s' = 10\ cm^{-1}$

$$\delta = \frac{1}{\sqrt{3\times0.1(0.1+10)}} = \frac{1}{\sqrt{3.03}} = 0.57 \text{ cm} = 5.7\text{mm}$$

(approximately)

Case 2: NIR light at 950nm

Given
$\mu^a = 0.1\ cm^{-1}$
$\mu'_s = 08\ cm^{-1}$

$$\delta = \frac{1}{\sqrt{3\times0.1(0.1+8)}} = \frac{1}{\sqrt{2.43}} = 0.64 \text{ cm} = 6.4\text{mm}$$

(approximately)

This improvement demonstrates how longer NIR wavelengths and reduced scattering in tissue can significantly enhance the efficacy of OLED-based photodynamic therapy (PDT) by reaching deeper-seated tumour.

3.2 Smart photosensitizers with nanotechnology

Nanotechnology enhances PDT specificity through smart photosensitizers encapsulated in nano-carries (e.g., liposomes, micelles, or polymeric nanoparticles). These carries are designed to respond to tumour-specific triggers, such as low pH (6.5-6.8 in tumours vs 7.4 in healthy tissues), overexpressed enzymes (e.g., matrix metalloproteinases), or elevated temperatures. Upon reaching the tumour, the nano-carries release photosensitizers, ensuring localized activation and minimizing damage to healthy cells.

For examples, pH-responsive nanoparticles conjugated with chlorine release the photosensitizer in acidic tumour microenvironments, achieving >90% drug release at pH 6.5 and 10% at pH 7.4. This targeted delivery enhances therapeutic efficacy and reduces systematic toxicity.

Nanoparticles-encapsulated PSs, such as gold nanorods or up conversion nanoparticles, enhance tumour targeting and ROS production [5]. Smart PSs could respond to tumour-specific biomarkers, ensuring precise delivery. Multifunctional nanoparticles integrating PSs with imaging agents enables simultaneous PDT and photodynamic diagnosis (PDD).

Example 2: ROS generation efficiency
The ROS generation rate is given by

$$R_{ROS} = \Phi \times [PS] \times I \times k$$

Where:
Φ= Quantum yield of the photosensitizer (unitless)
[PS]= Photosensitizer concentration (inμM)
I= Light intensity (in mW/cm^2)
k= System Constant (accounts for other proportional factors, here taken as 0.01)

Case 1: With nano-particles
$\Phi = 0.8$
[PS] = $10\mu M$
I= 100 mW/cm^2
k= 0.01
$R_{ROS} = 0.8 \times 10 \times 100 \times 0.01 = 8\mu M/s$

Case: Without nano-particles
$\Phi = 0.5$
[PS] = $10\mu M$
I= 100 mW/cm^2
k= 0.01
$R_{ROS} = 0.5 \times 10 \times 100 \times 0.01 = 5\mu M/s$

Enhancement = $\frac{8-5}{5} \times 100\% = 60\%$
Hence, Nanoparticle enhance ROS production by 60%, which can significantly improve the therapeutic efficacy of PDT by increasing oxidative damage to tumour cells.

3.3 AI-Driven optimization
Artificial intelligence can optimize PDT by analysing patient data to tailor light intensity, wavelength and PS dosage [6]. AI-enhanced PDD improves tumour detection accuracy, while closed-loop system integrating OLEDs with biosensors adjust light delivery in real-time.

Example 3: AI-optimized light dosage
The optimal light dose D is calculated as:

$$D = \frac{E}{A}$$

Where:
D = Light dose (J/cm^2)
E = Energy delivered(J)
A = Treatment area cm^2

AI-predicted energy equation
The energy delivered E is predicted using the following model:

$$E = \alpha \times e^{kd}$$

Where:
α = Photosensitizer absorption coefficient
k = Attenuation factor (m^{-1})
d = tumour depth (mm)

Given values
d = 5mm
α = 0.9
k = 0.2 m^{-1}
A = 10 cm^2

Calculated energy delivered
$E = 0.9 \times e^{0.2\times5} = 0.9 \times 2.718 = 2.45J$

Calculate dose
$D = \frac{E}{A} = \frac{2.45}{10} = 0.245\ J/cm^2$

Result
Predicted energy delivered = 2.45 J
Treatment area = 10 cm^2
Light dose: 0.245 J/cm^2

3.4 Bioadaptive wearable OLED devices
Ultra-thin OLED patches (6 μm thick) enable continuous PDT, improving patient compliance [2]. Bio-adaptive devices with biosensors monitor oxygen levels or PS concentrations, adjusting light output.
Glucose-based bio-fuel cells ensure long-term functionality.

Table 1: Comparison of Wearable OLED configurations

Feature	Current OLED patch	Bio-adaptive OLED patch
Thickness	$10\mu m$	$6\ \mu m$
Light output (mW/cm^2)	50	80
Biosensor integration	No	Yes
Power source	Battery	Biofuel cell
Treatment duration	1-2 hours	Continuous

3.5 Optogenetic-inspired PDT
Inspired by optogenetics, PDT could use genetically engineered tumour cells expressing light-sensitive proteins activated by OLEDs to trigger apoptosis without traditional PSs [6]. This approach eliminates PS toxicity and enables ultra-precise targeting.

3.6 Quantum Dot- Enhanced OLEDs
Quantum dot (QD)-enhanced OLEDs offer narrow spectral bandwidths and high brightness, enabling precise PS activation [2]. QD-OLED hybrids could switch wavelengths dynamically, targeting multiple PSs in a single session.

Example 4: QD-OLED spectral tuning
The emission wavelength λ of a QD-OLED depends on quantum dot size:

$$\lambda = \left[\frac{hc}{(E_g + \frac{\hbar^2\pi^2}{2md^2})}\right]$$

Where:
λ = Emission wavelength (in mm)
h = Plank constant
c = Speed of light

$\hbar = \frac{h}{2\pi} = \frac{6.67\times10^{-34}}{3\times10^{8}} = 2.2233\times 10^{-42}$

E_g= Band gap (in eV)
m = Effective mass of electron
d = diameter pf quantum dot (in nm)

Case 1: QD Size 5nm
Given
d = 05nm
E_g= 1.5eV
m = 0.1

$$\lambda = \left[\frac{hc}{(E_g + \frac{\hbar^2\pi^2}{2md^2})}\right]$$

$$\lambda = \left[\frac{6.67 \times 10^{-34} \times 3 \times 10^{8}}{(1.5 + \frac{(2.2233 \times 10^{-42})^2 \times (3 \times 10^{8})^2}{2 \times 0.1 \times (0.5)^2})}\right]$$

$$\lambda = 1.334 \times 10^{-25}\text{m}$$

4. Schematic diagram of futuristic OLED-PDT system

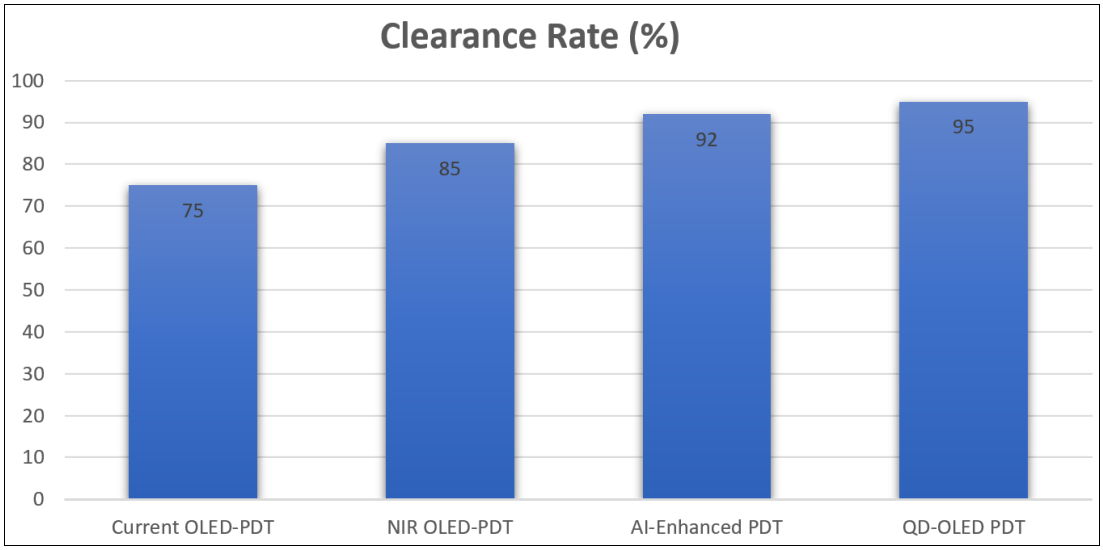


Fig 1: A futuristic OLED-based PDT system integrates NIR OLEDs, nanoparticle-enhanced PSs, biosensors and AI-control. The flexible OLED patch delivers uniform NIR light, while AI optimizes treatment in real-life

5. Efficacy trends in OLED-based PDT

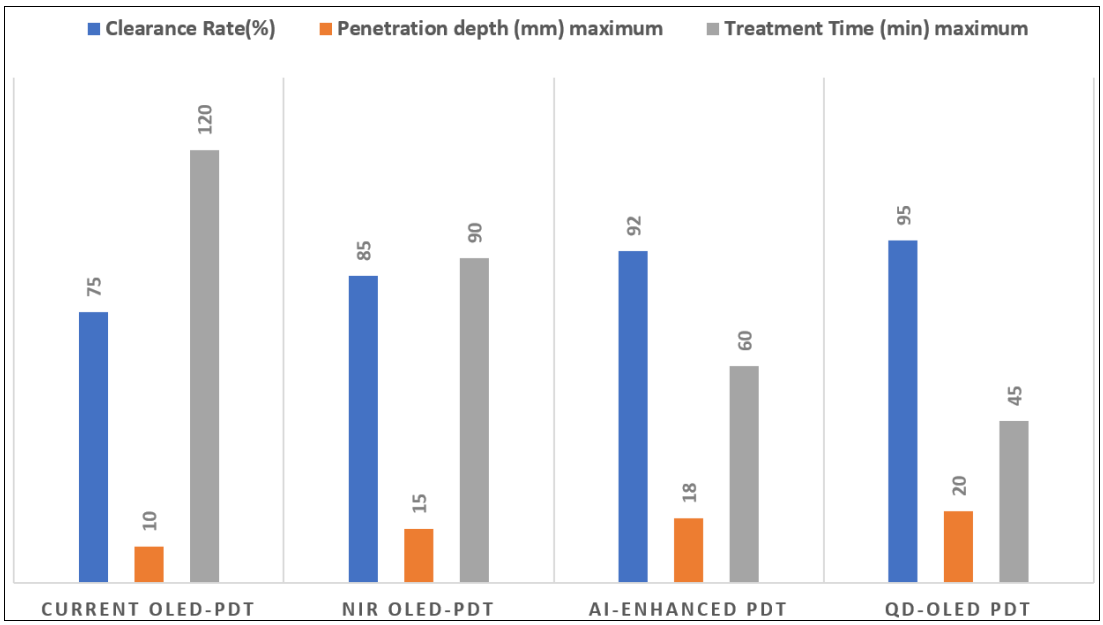


Fig 2: Projected efficacy trends for OLED-based PDT systems, comparing current and future technologies

Chart JS configuration

PDT system type	Tumour clearance rate (%)
Current OLED-PDT	75
NIR OLED-PDT	85
AI-Enhanced PDT	92
QD-OLED PDT	95

Table 2: Efficacy metrics for OLED-PDT systems

System type	Clearance Rate (%)	Penetration depth (mm)	Treatment Time (min)
Current OLED-PDT	75	5-10	60-120
NIR OLED-PDT	85	10-15	45-90
AI-Enhanced PDT	92	12-18	30-60
QD-OLED PDT	95	15-20	20-45

6. Ethical and practical considerations

As advanced OLED-based photodynamic therapy (OLED-PDT) systems integrate artificial intelligence, nanotechnology and biosensing, several ethical and practical challenges arise that must be addressed before widespread clinical adoption.

6.1 Data privacy and AI integration

The incorporation of AI models in OLED-PDT especially for dosage prediction, real-time feedback, or patient-specific treatment planning-requires the collection of sensitive medical data. This raises critical issue related to:

- Data ownership and consent
- Secure storage and transmission
- Algorithm transparency and accountability

Ensuring compliance with healthcare data regulations (e.g. HIPAA, GDPR) and adopting explainable AI models is essential to build trust in clinical settings.

6.2 Equity and accessibility

Nanotechnology-based therapies and AI-driven OLED patches may not be equitably distributed, especially in low-resource settings. High development costs, limited infrastructure, and a lack of specialized personnel could restrict access. This demands:

- Subsidies or public-private partnerships to reduce cost
- Development of scalable and affordable variants
- Inclusion of underrepresented populations in clinical trials.

6.3 Long-term biocompatibility and safety

While nanoparticles and gene-modifying tools can enhance ROS production and specificity in PDT, their long-term effects remain under investigation. Concerns include:

- Bioaccumulation of quantum dots or metal-based PSs
- Unexpected immunogenic or toxic responses
- Genetic interventions that may alter normal cellular function

6.4 Regulatory oversight and standardization

There is an urgent need to develop global regulatory frameworks that:

- Define safety thresholds for light exposure, PS dosage, and nanoparticle concentration
- Ensure cross-border standardization for OLED device specifications
- Monitor use of unofficial or unregulated sources of nanomaterials and genetic tools

Collaboration among international health bodies (e.g. WHO, FDA, EMA) can help streamline evaluation protocols and ensure ethical compliance.

7. Conclusion

The future of OLED-based Photodynamic Therapy (PDT) represents a transformative leap in precision oncology, addressing critical limitations of current cancer treatments through innovative integration of advanced technologies. Next-generation Near-Infrared (NIR) OLEDs enhance tissue penetration, enabling effective treatment of deep-seated tumours like pancreatic or brain cancers.

Nanotechnology-driven smart photosensitizers improve tumour specificity and ROS production, while AI-driven optimization personalizes treatment parameters for optimal efficacy. Bioadaptive wearable OLED devices offer patient-friendly, continuous therapy and optogenetic-inspired approaches promise ultra-precise targeting without traditional photosensitizers. Quantum dot-enhanced OLEDs further refine spectral precision, expanding PDTs versatility across complex cancers.

As illustrated by schematics, efficacy trend charts and solve examples, these advancements collectively improve tumour clearance rates (projected to reach 95% with QD-OLED PDT), deepen light penetration (up to 20mm), and reduce treatment times. However, ethical challenges, including data privacy, equitable access and long-term safety of nanomaterials must be addressed. Robust regulatory frameworks and interdisciplinary research are essential to translate these innovations into clinical practice.

By overcoming current barriers, OLED-based PDT has the potential to redefine cancer care, offering minimally invasive, highly personalized and effective solutions for diverse malignancies, paving the way for a new era in oncology.

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