



Electrospinning vs Fluorescent Organic Nano-Dots: A Comparative Review of Nanotechnologies in Organoluminophores Utilization

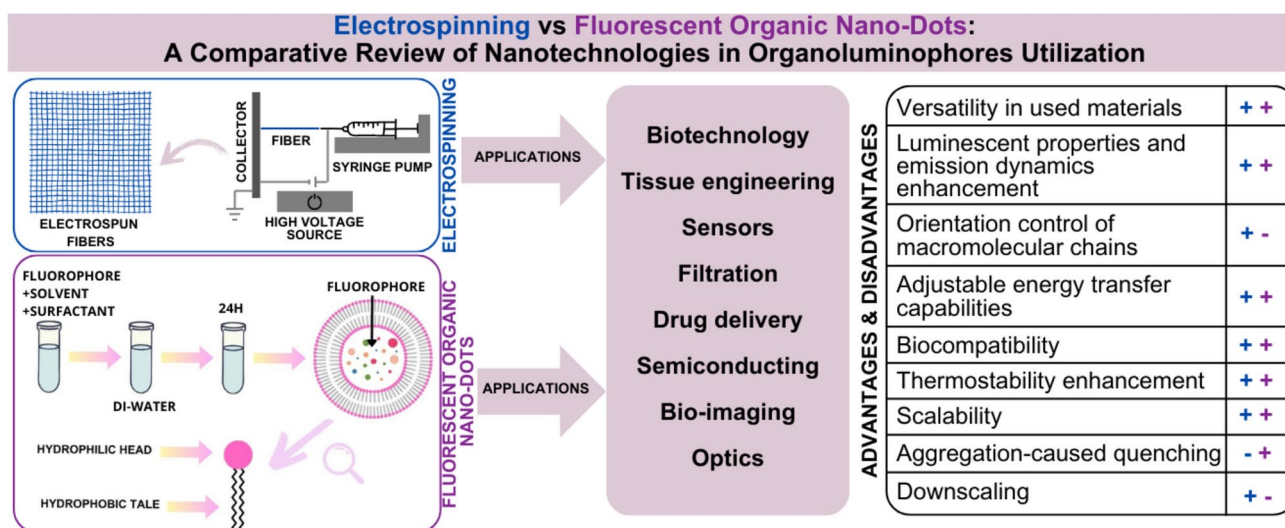
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Abstract

This review explores the pivotal roles of two advanced nanotechnologies—electrospinning (ES) and fluorescent organic nano-dots (FONs) in the development and application of organoluminophores (OLs). As demand intensifies for innovative OL-based systems in fields such as biomedical imaging, drug delivery, materials engineering, sensing, and energy, ES and FONs present complementary yet distinct technological pathways. Each method offers unique advantages in optimizing material properties, compatibility, and optical performance, positioning them at the forefront of OL-based research. ES enables precise control over material structure, enhancing performance for scalable industrial applications. FONs deliver superior optical properties, particularly for bio-imaging, through environmentally friendly synthesis. This comparative analysis critically examines the strengths and limitations of both techniques, including aspects of synthesis complexity, material adaptability, functional enhancement, and industrial utilization. Furthermore, recent advancements, ongoing challenges, and future prospects within this rapidly evolving field are discussed, providing a comprehensive perspective on the potential of these luminescent technologies to drive next-generation OL applications.

Graphical Abstract



Keywords Electrospinning · Electrospun fibers · Fluorescent organic nano-dots · Organic fluorophores · Organoluminophores · Organic semiconductors

Abbreviations

ES	Electrospinning
FON	Fluorescent organic nano-dot
OL	Organoluminophore
NP	Nanoparticle
OLED	Organic light-emitting diode
CCL	Color conversion layer
PVA	Poly vinyl alcohol
XRD	X-Ray diffraction analysis
FTIR	Fourier-transform infrared spectroscopy
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
AFM	Atomic force microscopy
PL	Photoluminescence
PPV	Poly(p-phenylene vinylene)
PFO	Poly(9,9-dioctylfluoreny-2,7-diyl)
MEH-PPV	Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene]
PMMA	Poly(methyl methacrylate)
FE-SEM	Field emission scanning electron microscope
PEO	Poly(ethylene oxide)
P3HT	Poly(3-hexylthiophene)
PLA	Poly(lactide)
CPNP	Conjugated polymer nanoparticle
CN-MBE	1-Cyano-trans-1,2-bis-(4'-methylbiphenyl)-ethylene
UV	Ultraviolet
TLC	Thin layer chromatography
polyDOPA	Poly(3,4-dihydroxyphenylalanine)
TADF	Thermal activation delayed fluorescence
AIE	Aggregation-induced emission
AIDF	Aggregation induced delayed fluorescence
ACQ	Aggregation-caused quenching

1 Introduction

Electrospinning method is currently at the forefront of research [1–4] and industrialization of fiber-based polymer materials due to its attractive properties such as the huge length-to-diameter ratio, the ability to produce smooth nanofibers, and the ease of manipulating the composition and properties of the fibers being formed.

Compared with other methods of manufacturing nanoscale fibers (e.g. drawing, coating, printing [5]) ES is a fairly automated, versatile, and affordable method, that has been constantly developing. Although the concept of electrospinning was developed back in the sixteenth century, its practical application has become widespread only in the last two decades. This innovative method has found wide application in various fields, including tissue engineering [6], sensor technology [7], drug delivery systems [8], fluorescent semiconductor development [9], biotechnology [10], filtration processes [11] and many other fields (Fig. 1 left). Depending on the type of their laying, electrospun fibers can be used to form membranes that will be characterized by good flexibility and mechanical strength, porosity, as well as hydrophobic and catalytic properties [12]. The introduction of various additives into polymer matrices helps to increase thermostability, fiber formation capacity, and luminescence capability. The inclusion of inorganic compounds (e.g., metal ions [13]), organic dyes (e.g., fluorescent dyes [14]) or π -conjugated polymers [15] can purposefully change both physical and chemical properties. OL's, being semiconductors, serve as promising additives for research involving electrospun fibers, showing considerable potential and wide application in various fields [16–18].

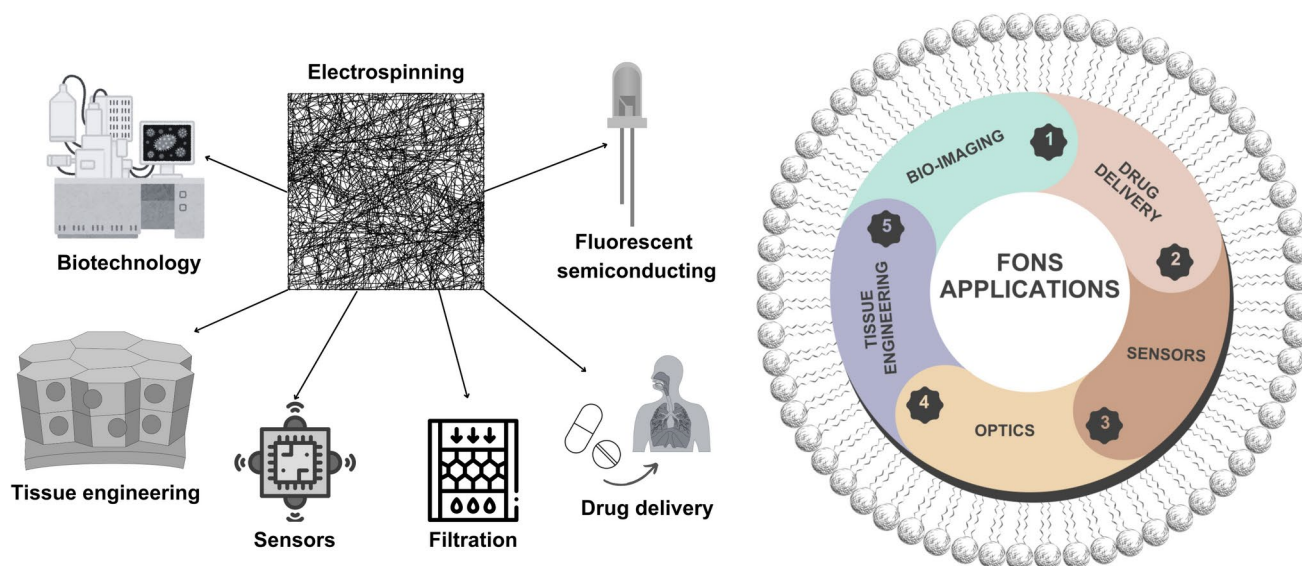


Fig. 1 Electrospinning [6–11] and fluorescent organic nano-dots applications [25–28]

This review focuses on electrospinning as the primary technique for creating polymer nanofibers with unique characteristics. Compared to other methods, electrospinning is highly adaptable, cost-efficient, and widely adopted, with the added benefit of being automated. Through the addition of various modifiers, properties of electrospun fibers can be tailored, making them particularly suitable for applications involving organoluminophores (OLs) across scientific and industrial domains. In this article, we explore the use of electrospinning specifically for incorporating OLs into fibrous structures. OLs offer high luminescence and a broad spectral range, positioning them as valuable components in functional light-emitting materials. Electrospinning allows for the uniform embedding of organic luminescent molecules in nanofibers, enhancing brightness stability. Furthermore, the flexibility of this method in shaping material morphology and tuning optical properties broadens the potential applications of OLs in fields such as sensor development, biomedical imaging, and flexible electronics.

Nanoparticles (NPs) are valuable tools in biochemistry, pharmacy, and biomedical sciences. Their small size allows unique characteristics to emerge, vastly different from bulk materials. Like electrospun fibers, characterized by a high surface-to-volume ratio and unique chemical properties, NPs find applications in biomedical fields like drug delivery, imaging, and diagnostics [19–21]. The development of organic dye nanoparticles makes a major breakthrough in fluorescence research. Organic dyes exhibit fluorescence through two mechanisms: resonant transitions and charge-transfer (CT) transitions. Resonant dyes, such as fluoresceins and rhodamines, are characterized by well-defined, narrow absorption and emission spectra with small Stokes shifts. On the other hand, solvent polarity has a significant impact on the bigger Stokes shifts and wider, structureless bands displayed by CT dyes such as coumarins. Early attempts to produce organic dye nanoparticles encountered difficulties because of their limited thermal stability and mechanical strength relative to inorganic materials. A breakthrough came in the 1990s when Nakanishi and collaborators introduced the “reprecipitation method,” facilitating the systematic synthesis of organic dye nanoparticles. This innovation led to the discovery of size-dependent photophysical properties, including fluorescence, in various organic systems. Subsequent research has expanded these methodologies, introducing a wide array of organic dyes and fabrication strategies, thereby enhancing the versatility and application potential of fluorescent organic nanoparticles [22–24]. Nowadays, there’s increasing interest in enhancing nanoparticles for bioimaging, biosensing, optics, and more [25]. This review focuses on FONs, i.e., fluorescent organic nanoparticles, which are versatile nanostructures emitting light across spectra, offering diverse applications

in biology and medicine, with potential for combined diagnostics and therapy (Fig. 1 right) [25, 26].

FONs propose several significant advantages over other materials. One of many is their better stability, biocompatibility and better light scattering effect. Additionally, compared to nanoparticles made from metals and inorganic compounds, organic nanoparticles are cheaper, can be prepared in a simple way and have a high possibility of modification by inserting other functional groups [25, 27].

Luminescent nanoparticles from conjugated polymers address processing challenges, especially in multilayer devices [28]. Synthesizing them via dispersed system polymerization offers advantages like access to stable materials for tasks such as cell imaging and creating nanocomposites. These nanoparticles are recognized for their potential in cell imaging. Despite their wide use in organic light-emitting diodes (OLEDs) and color conversion layers (CCLs), fluorescent and phosphorescent compounds are not extensively researched, highlighting the importance of further analysis [26].

In our review, we aim to thoroughly examine the strengths and weaknesses of both methods concerning their effectiveness in organic fluorophore technology. By analyzing aspects such as manufacturing complexity, compatibility with semiconductors and other materials, as well as the enhancement of optical properties, we can determine their suitability for specific applications. Additionally, we will explore the latest trends, achievements, challenges, and prospects in this area, providing insights into the evolving industry of organic semiconductor technologies.

1.1 Background

Electrospinning, originally termed electrostatic spinning, has its conceptual roots in the sixteenth century, when the Royal College of Physicians observed the formation of a cone and ejection of droplets from a water drop near a charged piece of amber—a precursor to the modern Taylor cone. It wasn’t until the early twentieth century that electrospinning was formally recognized for its potential to produce fibers, leading to its first patent [29]. Since then, the technology has evolved significantly, with rapid advancements over the past few decades transforming it into a highly versatile method for fabricating nanofibers with intricate structures. These developments have not only refined the technique but also expanded its applications, fostering innovations in fields ranging from materials science to biomedicine [30].

Electrospinning is a technique for micro- and nano-scale fiber fabrication from polymer solutions. Using an appropriate voltage applied to the steel needle and adjusting the process parameters, morphologically different types of fibers can be produced. In modern times, a vast array of

electrospinning machine variations has been developed, ranging from needleless to ultrasound-enhanced designs. Nevertheless, all these systems operate on a similar fundamental principle. Figure 2 (left) illustrates a basic electrospinning setup, consisting of a syringe pump (A) that ensures a constant flow of solution through a steel needle (B). High voltage (C) generates electrostatic forces that pull the solution into a Taylor cone, ejecting fine fibers that deposit on a collector (D). The formation of fibers depends on solution's parameters such as viscosity, conductivity, and surface tension. The needle size influences fiber diameter, while flow rate must be carefully regulated to avoid droplet formation or jet interruption. The collector type also plays a critical role: a flat, stationary collector produces randomly oriented fibers, while rotating or patterned collectors can align or structure the fibers. Optimizing these factors is crucial, as each adjustment impacts the morphology, diameter, and uniformity of the electrospun fibers.

The first use of nanoparticles dates to the fourth century AD. A cup found from that time, made of special glass containing gold and silver nanoparticles with the addition of copper, emitted a different glow at a certain angle [31].

The use of nanoparticles in scientific research has progressed significantly over the years, with studies demonstrating their wide-ranging applications and potential benefits. The connection between nanoparticles and biomedicine was established in the late 1970s, and by 2005, nearly thirty papers referred to this topic. Within a decade, Web of Science published over 1000 articles on nanomedicine in 2015, with a majority focusing on nanoparticles (NPs) for biomedical applications. Advanced forms of nanoparticles (NPs) include nanocarriers such as dendrimers, liposomes,

peptide-based nanoparticles, carbon nanotubes, quantum dots, polymer-based nanoparticles, inorganic vectors, lipid-based nanoparticles, hybrid NPs, and metal nanoparticles. Nanoparticles are a new and growing area of research fields like delivering medicine, studying tiny fluids, making sensors, analyzing tiny samples, and engineering tissues for treating diseases better [32–35]. Fluorescent organic nano-dots are one branch of nanoparticle development.

Despite the existence of many methods of producing nanoparticles, the most successful and simple approaches are solvent evaporation, emulsification or nanoprecipitation [26]. There are various approaches to acquiring FONs, depending on the preferred structure and intended use. Numerous methods exist for obtaining nanoparticles, but not many consist of fluorophores.

FONs can be created through the precipitation of the fluorophore solution upon mixing with water. The incorporation of a surfactant enables micelles to encapsulate the fluorophore particles during precipitation, facilitated by the interaction between the hydrophobic tails of the surfactant and the nonpolar fluorophore molecules (Fig. 2). Surfactant is intended to minimize the surface energy of small particles. In the absence of surfactant, surface energy is minimized during the formation of large fluorophore particles. There are different methods of creating FONs, some are very simple, while others are more demanding.

Emulsions are solutions of immiscible liquids, categorized by their size into micro-emulsions (10–100 nm), mini-emulsions (100 nm–1 μ m), and macro-emulsions (>1 μ m). Nano-emulsions fall between micro- and mini-emulsions and can be created using low or high energy methods. Low energy emulsification relies on spontaneous processes,

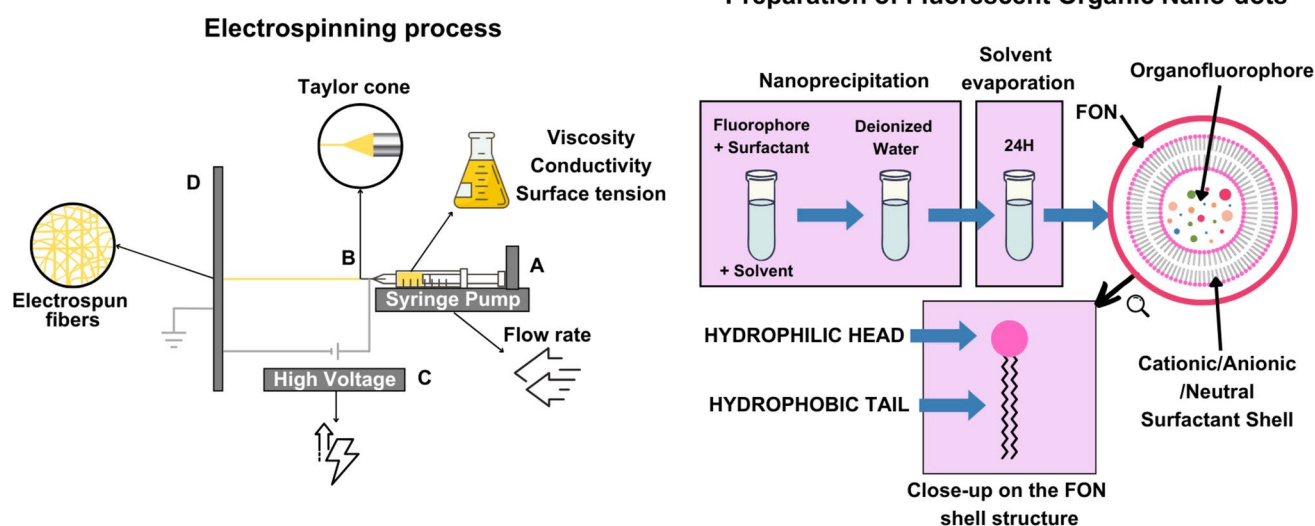


Fig. 2 Schematic representation of the basic electrospinning setup (left), illustrating: **A** syringe pump, **B** steel needle, **C** high voltage source, and **D** collector, along with the parameters influencing fiber

properties. On the right, the synthesis method and structural representation of a single fluorescent organic nanoparticle (FON) are shown

while high energy emulsification involves vigorous mixing to disperse one substance into microscopic droplets within another. These methods are crucial in industries like food, pharmaceuticals, and cosmetics for achieving precise product quality and consistency. Generating nanoparticles from emulsions involves eliminating solvents through methods like evaporation, salting-out, or diffusion. Overall, these methods offer cost-effective ways to obtain nanoparticles with significant advantages [36].

Thus, based on the methods of producing electrospun fibers and fluorescent nanoparticles, both approaches are relatively straightforward to implement, making them advantageous in terms of manufacturability. Their respective strengths and limitations are further discussed below, supported by the latest scientific studies.

2 Advantages and Disadvantages of Both Methods

2.1 Versatility in Used Materials

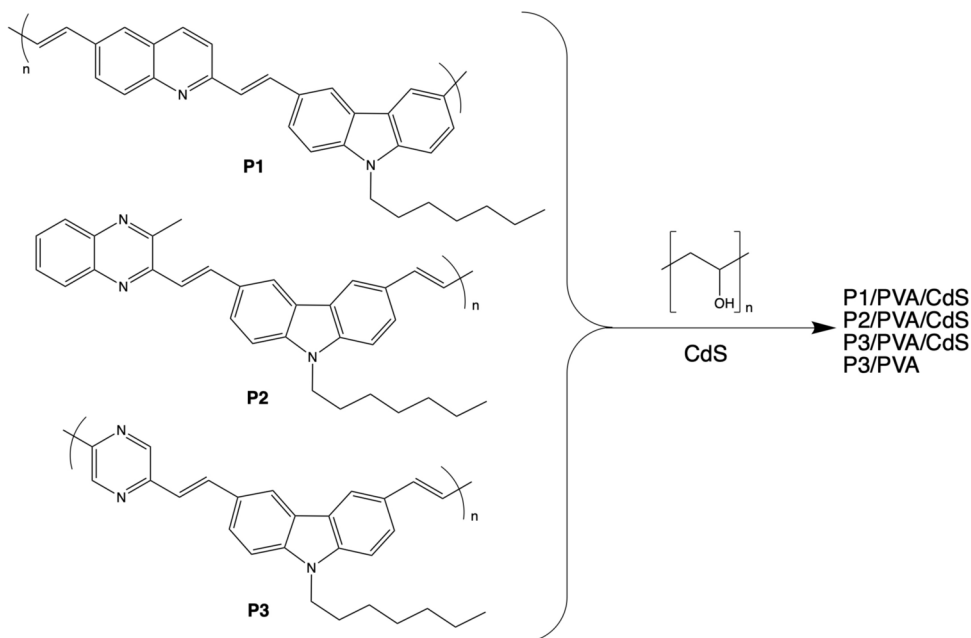
The flexibility in material selection for the disposal of OLs offers researchers a broader spectrum of options for optimizing the efficiency of nanotechnology applications. This adaptability facilitates the development of innovative strategies for recycling and waste management, allowing for the effective degradation and recovery of valuable components. By integrating various organic and inorganic materials, scientists can enhance sustainability and effectiveness in utilizing organic luminescent materials, which ultimately propels

advancements in the field of nanotechnology and its environmental applications.

In the study conducted in 2023 [37], the integration of a copper-based complex into a poly(methyl methacrylate) (PMMA) matrix demonstrates the potential of electrospinning to create hybrid organic–inorganic nanofibers with tailored photoluminescent properties. A tetrakis((μ 3-N-(3,5-dichlorosalicyclideneamino)ethanolato)-Cu(II)) was synthesized and incorporated into PMMA via electrospinning to form Cu@PMMA nanofibers with diameters ranging from 148 to 307 nm. Under UV excitation, both the complex and nanofibers exhibited blue emission. The photoluminescence (PL) intensity of the nanofibers increased with Cu²⁺ concentration, peaking at 15 wt.% before declining due to concentration quenching. Temperature-dependent PL measurements (10–300 K) revealed a decrease in emission intensity due to thermal quenching. These nanofibers, with high chromaticity values, show promise for blue solid-state lighting applications. The ability to fine-tune the composition and structural properties of such hybrid nanofibers demonstrates electrospinning's potential in developing advanced materials for optical and solid-state lighting technologies.

In a 2021 study, P.S. Umabharathi and S. Karpagam demonstrated the versatility of electrospinning method by successfully integrating cadmium sulfide (CdS) as an inorganic component with conjugated polymers and carbazole-based compounds as organic luminophores (Scheme 1). The researchers found that this combination facilitated good dispersion and compatibility within the electrospinning process, leading to enhanced photoluminescent properties and thermal stability. Spectroscopic analyses revealed a red

Scheme 1 Synthesis of conjugated polymers [38]



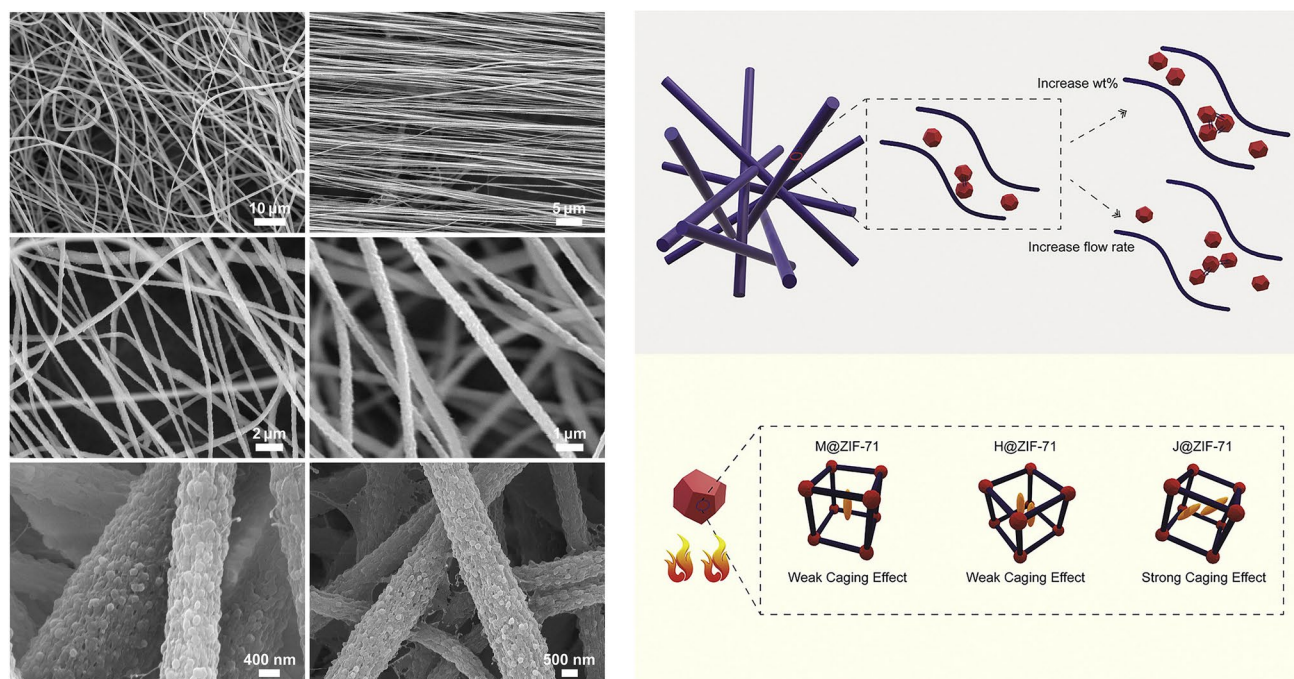
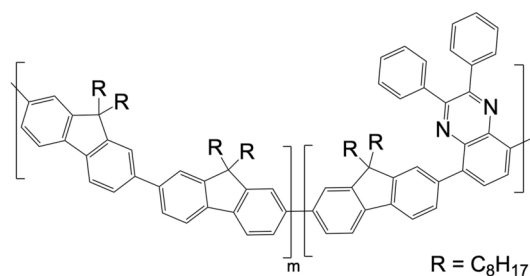


Fig. 3 Electrospun fibers (left) with incorporated rhodamine-doped metal–organic frameworks (right) [39]. Reproduced under terms of the CC-BY-NC-ND 4.0 license, 2021, Cell Press

shift in emission, indicating effective interaction between the organic and inorganic components. The electrospinning method effectively harnesses the unique properties of both organic luminophores and inorganic CdS, as also compatibility with conjugated polymers and macromolecular organic molecules, enabling advanced applications in optoelectronics.

In another study of the same year [39], researchers investigated the creation of luminescent electrospun fibers by incorporating rhodamine-doped metal–organic frameworks (MOFs) within a polymer matrix (Fig. 3). MOFs are a promising class of crystalline materials with tunable porosity, high surface area, chemical stability, and diverse functional groups, making them ideal for applications in gas separation, catalysis, drug delivery, and advanced technologies [40]. The results of the study demonstrated that the electrospun rhodamine@MOF/polymer fibers achieved an impressive quantum yield, underscoring the versatility of the electrospinning method in integrating both organic luminescent dyes and inorganic frameworks, as also the MOFs themselves as separate group of materials, to enhance luminescent properties. This synergy not only improves luminescence but also ensures thermal stability, allowing the fibers to retain their luminescent characteristics even at elevated temperatures, making them suitable for a wide range of applications.

The next study [41] highlights the versatility of electrospinning method in integrating both organic and



Scheme 2 Chemical structure of polyquinoxaline [41]

inorganic materials to create highly functional hybrid sensors. Researchers developed a novel chemical warfare agent sensor by immobilizing polyquinoxaline based conjugated polymer dots (CPdots) (Scheme 2) on poly(vinyl alcohol) (PVA)-silica electrospun nanofibers, resulting in a dots-on-fibers (DoF) structure. The electrospinning process enabled stable electrostatic interactions between the amine-functionalized PVA-silica fibers and the CPdots, preserving the high emissive properties essential for sensitive detection. This DoF nanostructure exemplifies how electrospinning can be adapted to create rapid, portable sensors, with potential for other applications by simply altering the probe dots. Additionally, this research further confirms the capability of electrospinning to utilize macrocyclic compounds, expanding the scope of materials that can be integrated into hybrid sensor systems.

Similarly, as electrospinning method fluorescent organic nano-dots demonstrate remarkable versatility by effectively

incorporating both organic luminophores and inorganic elements to enhance functionality. In Khan et al.'s study [42], boron-containing organic luminophores (Fig. 4) were synthesized into FONs that acted as efficient color conversion layers (CCLs) for optoelectronic applications, converting short-wavelength light into specific wavelengths with precision. By introducing ionic and non-ionic surfactants, the researchers achieved high stability and water-processability in FONs, addressing challenges typically faced with inorganic quantum dots, such as instability and toxicity. This hybrid approach leverages organic and inorganic components for environmentally friendly, high-performance CCLs with superior color conversion efficiency and long-term stability, highlighting the adaptability of FONs across various optoelectronic applications.

Poly(styrene-co-maleic anhydride) (PSMA) based FONs with aggregation-induced emission (AIE) gen (9,10-distyrylanthracene) demonstrate same remarkable versatility by integrating organic and inorganic elements to develop highly sensitive and selective sensors (Fig. 5). In Jiang et al.'s study [43], the AIE-active organic dots were functionalized with inorganic components on their surface, creating an efficient “on-off-on” chemosensor for detecting metal ions such as copper (Cu^{2+}) and iron (Fe^{3+}). The interaction between the surface-bound inorganic materials and the organic AIEgen significantly enhanced the fluorescence response, allowing for the detection of metal ions with remarkable sensitivity. The reversible fluorescence response upon the binding of

cysteine highlights the adaptability of these hybrid AIE dots in dynamic sensing applications, establishing their potential for advanced environmental and biochemical monitoring. This study further demonstrates that FONs are capable of integrating inorganic and organic substances not only within the nanoparticles but also on their surface, significantly expanding the research landscape, particularly in the field of sensors.

According to those publications, there are no inherent material limitations when selecting components for both electrospinning and FONs methods. Studies demonstrate that each technique can effectively conjugate with a wide range of compounds, including large macrocyclic structures, polymers, and inorganic materials. This versatility underscores potential for diverse applications across various scientific and industrial fields either for ES or for FONs methods.

2.2 Luminescent Properties and Emission Dynamics Enhancement

In 2009, a group of scientists [44] carried out a study on light-emitting electrospun nanofibers derived from mixtures of three components: poly(9,9-dioctylfluorenyl-2,7-diyl) (PFO), poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV), and poly(methyl methacrylate) (PMMA) (Scheme 3). The morphology of the resulting matrixes was analyzed via field emission scanning electron

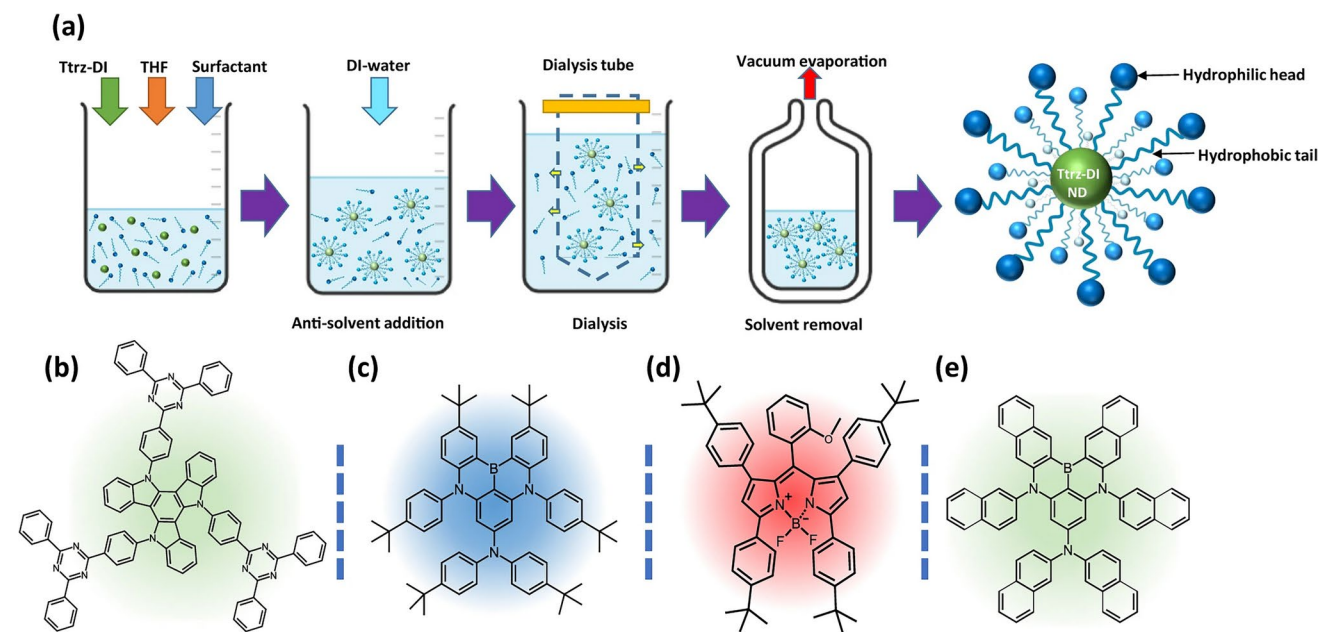


Fig. 4 The synthesis of fluorescent nano-dots **a** with different organoluminophores **b** 5,10,15-tris(4-(4,6-diphenyl-1,3,5-triazin-2-yl)phenyl)-10,15-dihydro-5H-diindolo[3,2-a:3',2'-c]carbazole, **c** 2,12-di-tert-butyl-N,N',5,9-tetrakis(4-(tert-butyl)phenyl)-5,9-dihydro-5,9-diaza-13b-boranaphtho[3,2,1-de]anthracen-7-amine,

d 1,3,7,9-tetrakis(4-(tert-butyl)phenyl)-5,5-difluoro-10-(2-methoxyphenyl)-5H-414,514-dipyrrolo[1,2-c:2',1'-f][1,3,2]diazaborinine, and **e**, N,6,10-tetra(naphthalen-2-yl)-6,10-dihydro-6,10-diaza-16b-boraanthra[3,2,1-de]tetracen-8-amine [42]. Reproduced under terms of the CC BY 4.0 license, 2022, Nature

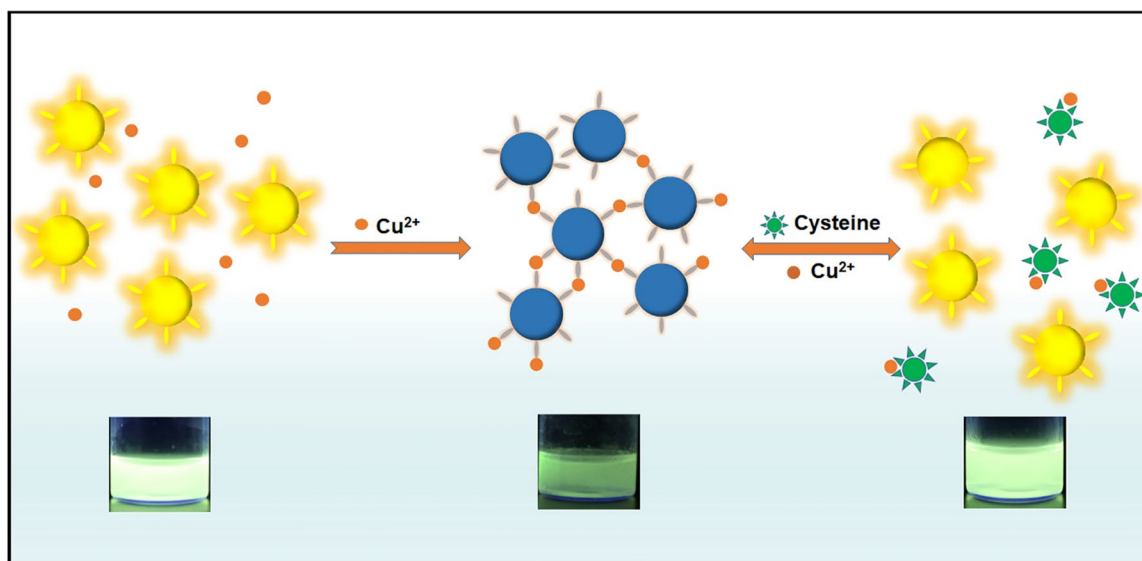
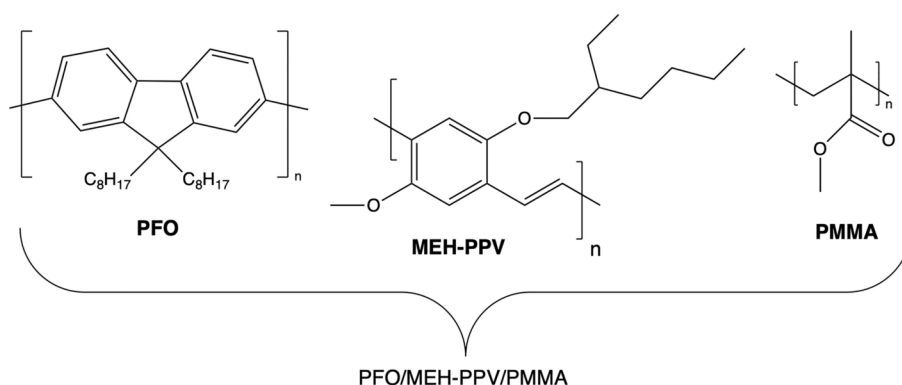


Fig. 5 The detection mechanism of AIE dots in the presence of Cu^{2+} and cysteine [43]. Reproduced under terms of the CC BY 4.0 license, 2018, MDPI

Scheme 3 Chemical structure of photoluminescent conjugated polymer [44]



microscope (FE-SEM) and fluorescence microscopy. Photoluminescent analysis revealed that the emission colors of the PFO/MEH-PPV/PMMA mixture shifted from blue to white, yellowish-green, greenish-yellow, orange to yellow with an increase in MEH-PPV content. Conversely, films obtained by another method, mainly by spin-coating, emitted colors ranging from blue to orange, pink-red, red and deep-red. This difference likely stems from solubility parameters, as two of the three components are blending with each other and trapped in the PMMA matrix, enabling energy transfer between PFO and MEH-PPV. The polymer domains in electrospun fibers were significantly smaller than in spin-coated films, resulting in different emission colors and increased luminescence efficiency. Additionally, fibers made via electrospinning exhibited higher photoluminescence efficiency compared to the spin-coated ones. This study illustrates the versatility of electrospinning in producing light-emitting nanofibers with varied colors by optimizing semiconductor polymer compositions. The electrospun fibers exhibited enhanced luminescence efficiency and a broader range of

emission colors compared to spin-coated films. This highlights the significant impact of the electrospinning method in fabricating advanced light sources and sensor materials.

In another study [45], the relationship between photoluminescence polarization and electrospinning was investigated. By utilizing conjugated MEH-PPV and polyethylene oxide (PEO) polymers in a 1:2 ratio, aligned anisotropic fibers were successfully produced. The polarized emission was quantified using a fluorescent spectrometer equipped with excitation and emission polarizers. The polarization coefficient of photoluminescence (PL), which compares the intensity of light emitted parallel and perpendicular to the alignment direction, was found to be 13.3 for unstretched samples, surpassing recent studies. This indicates a strong directional preference in the emission of light. Upon stretching, this coefficient increased to 25, indicating the effectiveness of the two-step process involving alignment and stretching in fine-tuning polarization. The study demonstrated that electrospinning could yield highly polarized PL from aligned MEH-PPV/PEO nanofibers, with polarization

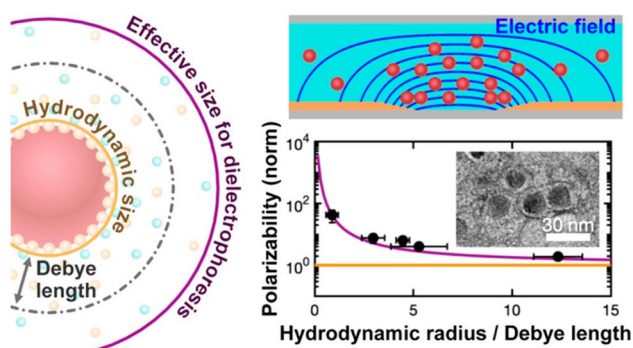


Fig. 6 Measurement of nanoparticle polarizability via fluorescence microscopy [46].

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adjustability achieved through mechanical stretching. This highlights the efficacy of electrospinning in enhancing photoluminescent polarization, potentially benefiting optoelectronic devices.

In 2019, researchers developed a novel method to quantify the polarizability of photoluminescent nanoparticles in water (Fig. 6), presenting experimental observations of the extraordinary polarizability exhibited by nanoparticles of commensurate size with the Debye screening length, which confirmed previously reported theory [46]. The Debye length measures how electric fields are screened in a medium, particularly in electrolyte solutions, and it quantifies the distance over which significant charge separation can occur due to the presence of mobile charge carriers like ions. Semiconductor quantum dots (QDs) served as ideal model nanoparticles to demonstrate this assay due to their tunable size and bright photoluminescence. The assay was based on microfluidic chambers with microelectrodes that

generated trapping potentials weaker than thermal energy. By comparing the local electric field strength and variations in QD concentration, the researchers computed the polarizability, which was found to agree with estimates based on the hydrodynamic diameter obtained using light scattering. Strikingly, the polarizability of the nanoparticles increased 30-fold in low salt conditions compared to high salt conditions, attributed to the increased thickness of the Debye layer relative to the particle radius. This study not only provided evidence that corroborated theoretical work studying direct solutions to the Poisson–Nernst–Planck equations but also offered an explanation for the previously observed conductivity dependence of biomolecule polarizability. Given the significance of nanoparticle polarizability for the electrically directed assembly of particles and their interactions with other materials in complex environments, the researchers anticipated that these results would be highly relevant to ongoing efforts in materials by design and nanomedicine.

In 2017 a group of researchers worked on developing conjugated polymer nanoparticles constructed with imidazole units (Fig. 7) [47]. The primary issue lies in the non-degradability of conjugated polymer nanoparticles (CPNPs), primarily stemming from their inert and carbon-based π -conjugated structure. This lack of degradability within conjugated polymer particle systems poses a significant obstacle to their safe use in vivo. The compounds they created addressed the issue by combining both intense fluorescence and biodegradability. CPNPs display hydrophobic characteristics and demonstrate minimal cytotoxicity. With their π -conjugated electron system, they emit strong fluorescence, offering tunable emission colors across the visible spectrum. CPNPs also serve as effective photoacoustic

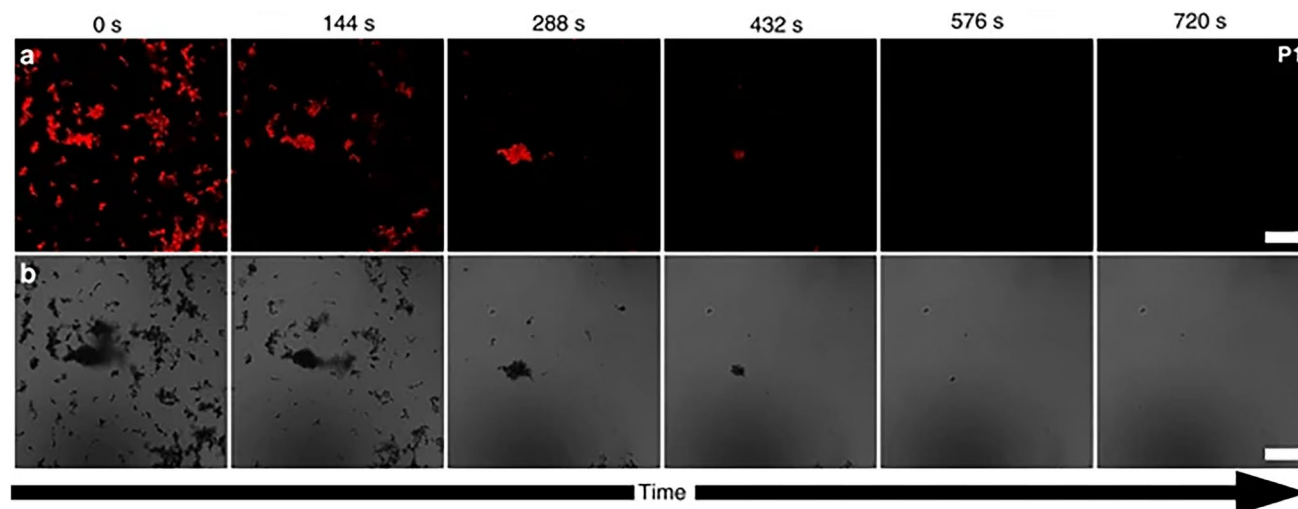


Fig. 7 Breakdown of Imidazole-Containing Conjugated Polymer Nanoparticles. In Figure a, Confocal fluorescence microscopy reveals the transformation of degradable particles P1 upon exposure to a 3 M H_2O_2 solution. After 12 min, fluorescent particle aggregates dissolve,

and individual particles vanish. The scale bar denotes 20 μm . Figure b shows corresponding bright-field images. Reproduced under terms of the CC-BY license, 2017, Nature [47]

contrast agents and are valuable in image-guided photodynamic and photothermal therapy. Their inherent semiconducting properties ensure exceptionally stable fluorescence, enabling prolonged detection periods. Furthermore, CPNPs can be customized with surface functionalization using biological recognition molecules like peptides, antibodies, and others. In this study, researchers have developed the ability to create conjugated polymer particles based on imidazole compounds that are biodegradable. Upon exposure to stimulated macrophages, the concentration of reactive oxygen species is adequate to degrade these particles. Compared to inorganic materials that undergo fluorescent degradation, conjugated polymer particles provide greater optical enhancement due to the dense packing of the luminophore. This allows for the potential use of conjugated polymer particles in biological and medical fields, such as imaging, drug delivery, and others. Tailored nanoparticles are utilized to precisely target specific biomolecular patterns on cell membranes, particularly in pathological conditions such as cancerous tumors.

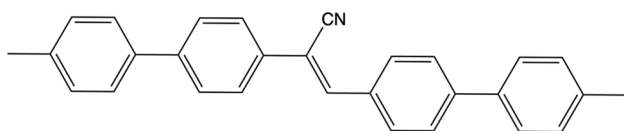
In 2002, [48] researchers conducted a study based on creating a new class of organic nanoparticles made of 1-cyano-trans-1,2-bis-(4'-methylbiphenyl)-ethylene (CN-MBE) (Scheme 4) with a diameter ranging from 30 to 40 nm. They were prepared by a simple reprecipitation method and exhibited strongly enhanced fluorescence emission. Researchers noticed that the CN-MBE nanoparticle emits very strong fluorescence, even though CN-MBE itself doesn't fluoresce much in a weak solution. CN-MBE exhibited a striking fluorescence intensity shift, transitioning from a non-fluorescent state as isolated single molecules in THF to a highly fluorescent suspension of nanoparticles in THF/water. This intensified emission from nanoparticles is clearly illustrated by the variations in the relative quantum yield (Φ_f) of CN-MBE ($2 \times 10^{-5} \text{ mol L}^{-1}$) across different proportions of THF/water mixtures. Isolated CN-MBE, up to 50% volume fractions of water addition, displayed virtually negligible fluorescence ($\Phi_f \approx 0.001$). At 80% volume fractions of water addition, the Φ_f value of the CN-MBE nanoparticle suspension was nearly 700 times greater compared to that of the CN-MBE solution in THF. The utilization of nanoparticles for on/off fluorescence switches was examined by comparing the fluorescent intensity in solution and nanoparticles. When illuminated with 365 nm UV light at room temperature, CN-MBE nanoparticles on the TLC plate exhibit vibrant blue fluorescence, which reversibly switches off in the presence

of dichloromethane vapor. This fluorescence switching characteristic introduces a fresh approach to nanoscale fluorescence switches capable of detecting organic vapors. Produced nanoparticles demonstrate significantly intensified light emission and on/off switching capabilities, enabling the detection of organic vapors. The increased fluorescence emission in CN-MBE nanoparticles is attributed to a combination of molecular flattening (planarization) and J-aggregation, a process where molecules stack closely together in an orderly manner, limiting unwanted energy loss and enhancing light emission.

In contrast to traditional organic dyes, fluorescent probes derived from nanoparticles boast increased brightness and improved photostability, proving their efficacy across various biological applications [49].

Xiaofeng Luo and others conducted a study focused on the synthesis of nanoparticles utilizing fluorescent dyes (DBQ-3PXZ) exhibiting both thermal activation delayed fluorescence (TADF) and aggregation-induced emission (AIE) properties [50]. To enhance the photostability of the fluorescent nanoparticles, two strategies were employed during their construction to get rid of the photobleaching of aggregation induced delayed fluorescence (AIDF) dyes. Nanoparticles were synthesized by physically incorporating an AIDF dye into an amphiphilic polymer via a reprecipitation technique. The first approach focused on isolating the AIDF dye component from molecular oxygen by optimizing the oxygen permeability of the amphiphilic polymer. The second approach involved the incorporation of low-molecular-weight antifade agents specifically designed to counteract the oxygen-mediated photodegradation of the AIDF dye. Drawing from the afore mentioned methodologies, a significant reduction in photobleaching of the desired fluorescent nanoparticles, while maintaining optimal brightness, was ultimately noted. The unique qualities of the resultant fluorescent nanoparticles, distinguished by their enhanced brightness, exceptional photostability, and extended excited-state lifespan, unmistakably designate this probe as an optimal candidate for biological fluorescence imaging. The initial fluorescence results obtained from living cells undeniably validated the feasibility of utilizing the feature-rich fluorescent nanoparticles for imaging purposes, showcasing an outstanding signal-to-noise ratio within the intracellular physiological environment.

The reviewed studies highlight significant advancements in enhancing luminescent properties and emission dynamics through electrospinning and fluorescent organic nanoparticles methods of nanomaterials production. By optimizing polymer compositions, researchers have achieved a wide range of emission colors and improved luminescence efficiency. Aligned nanofibers also exhibit notable photoluminescence polarization, enhancing their application potential



Scheme 4 Chemical structure of CN-MBE [48]

in optoelectronic devices. Additionally, biodegradable conjugated polymer nanoparticles combine strong fluorescence with biocompatibility, enabling innovative uses in medical imaging and targeted drug delivery. Overall, these advancements underscore the versatility of electrospinning and FONs, paving the way for future applications in advanced light sources and sensors.

2.3 Orientation Control of Macromolecular Chains

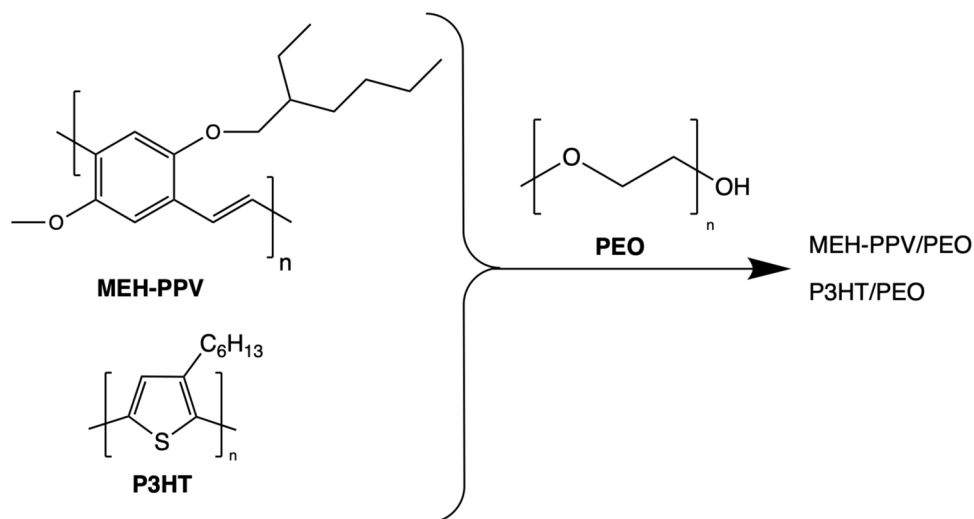
Orientation control of macromolecular chains in organoluminophores is crucial for optimizing their performance in optoelectronic applications. Proper alignment enhances photophysical properties such as absorption, emission, and quantum yield, while enabling polarized emission that improves display contrast. Additionally, controlled orientation facilitates exciton and charge carrier mobility, resulting in increased efficiency in devices. It also allows for the tuning of emission wavelengths and intensities, which is important for specific applications. Furthermore, well-aligned structures enhance stability and durability, ensuring long-term performance, and minimize unfavorable intermolecular interactions that can quench luminescence. Overall, effective orientation control is vital for maximizing the efficiency, stability, and tunability of organoluminophores, making them more suitable for advanced optoelectronic devices.

In a study conducted in 2011 [51] the effect of ES on photoluminescence and anisotropy was investigated using aligned nanofibers. Uniaxially aligned nanofibers were produced from two pairs of conjugated polymers via electrospinning: MEH-PPV/PEO and poly(3-hexylthiophene) (P3HT)/PEO (Scheme 5). The ratio of conjugated polymer to PEO by weight was 1:4, 1:10, 1:20, and 1:40. A U-shaped metal device was prepared to ensure well-aligned electrospun nanofibers. By manually moving the device back and

forth during the ES process, height-aligned nanofibers were collected between the metal legs. Luminescent polarization spectroscopy was employed to assess the anisotropy of emission from the resulting aligned conjugated polymer fibers. The findings revealed that the photoluminescence of aligned nanofibers exhibited strong anisotropy, with more intense emission along the axis of the nanofibers, while the PL of random nanofibers showed weak emission anisotropy. Moreover, the emission of random nanofibers shifted towards the blue spectrum with a decrease in the mass ratio of MEH-PPV/PEO, likely attributed to reduced aggregation of MEH-PPV macromolecular chains in the nanofibers. The intrinsically ordered and polycrystalline nature of P3HT in the solid state contributed to a higher luminescence anisotropy of aligned nanofibers compared to MEH-PPV/PEO. The results of the study suggest that electrospun conjugated polymer nanofibers possess macromolecular chains that are preferentially oriented along the axis of the nanofiber. Thus, electrospinning displayed as a promising method for precisely controlling the orientation of macromolecular chains within nanofibers, thereby influencing their optical properties.

Unlike electrospinning, the use of fluorescent nanoparticles does not enable the control of macromolecular chain orientation within the nanoparticles themselves, which presents a limitation of this method. Current literature primarily discusses the manipulation of nanoparticle orientation via electrospinning [52] or investigating the alteration of optical properties within nanoparticle clusters [53]. This lack of control over macromolecular orientation within fluorescent nano-dots underscores a disadvantage relative to the capabilities offered by electrospinning for achieving desired alignment and properties in luminescent materials.

Scheme 5 Synthesis of PEO co-polymers [51]

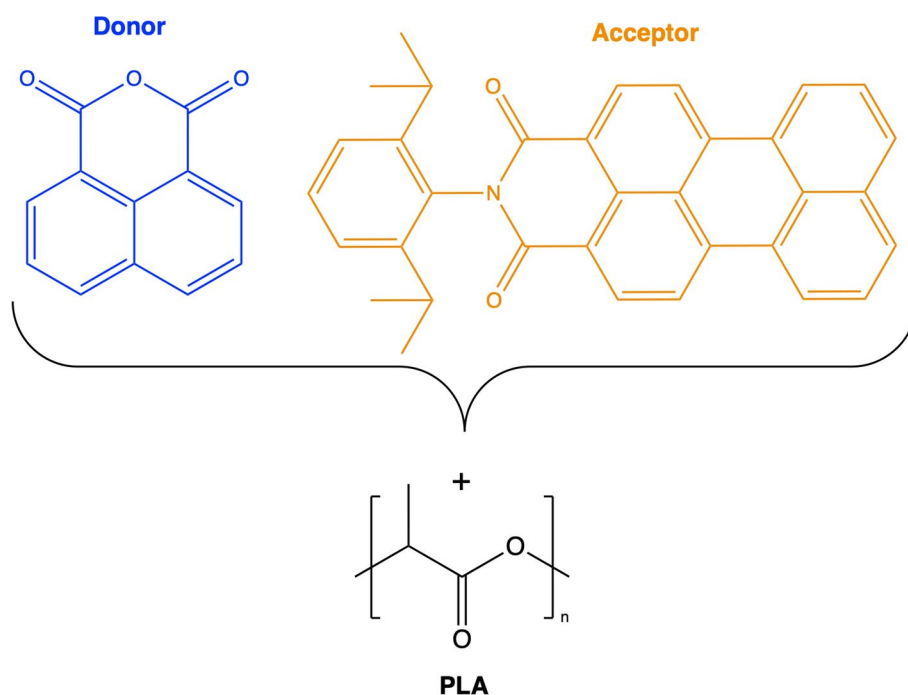


2.4 Adjustable Energy Transfer Capabilities

In their study [54], researchers selected coaxial electrospinning technology to produce a white-light-emitting porous fibrous membrane. This approach allowed for the spatial separation of blue energy donor (1,8-naphthalic anhydride) and orange energy acceptor (perylene mono-anhydride) fluorescent dyes (Scheme 6) within the membrane, effectively preventing energy transfer and resulting in uniform white light emission. They chose polylactide (PLA) as the matrix material due to its pore-forming capabilities, ensuring minimal interference with the fluorescent dyes and maximizing emission efficiency. Through adjustment of the dye concentration ratio, the researchers achieved efficient membrane preparation. The morphology of the fibrous membrane emitting white light was examined using SEM and TEM. PL spectra and lifetime measurements of the membrane were obtained using a fluorescent spectrophotometer, alongside the absorption spectra of fluorescent molecules captured using a fluorescence spectrometer. By introducing a porous surface structure using PLA, the interaction between the polymer matrix and the dye molecules was significantly reduced. The resulting membrane exhibited both flexibility and durability, indicating potential applications in next-generation lighting or display technologies. Through the utilization of coaxial electrospinning, the researchers successfully managed the energy transfer between donor and acceptor dyes, leading to the emission of uniform white light. This study demonstrates the capacity of electrospinning to finely tune optical properties and regulate energy transfer, particularly through the implementation of coaxial technology.

In 2015, Yang-Hsiang Chan et al. [49] outlined a trend in the advancement of semiconducting polymer dots, not only for biological imaging but also for sensing purposes. In a study conducted in 2009 [55] researchers described a new nanoparticle structure for oxygen sensing comprises p-conjugated polymer molecules doped with an oxygen-sensitive phosphorescent dye. When stimulated by light, the polymer effectively channels energy to the phosphorescent dye, yielding vivid phosphorescence that exhibits exceptional sensitivity to the levels of dissolved oxygen. Researchers proved the energy-transfer-mediated phosphorescence observed in metalloporphyrin-doped polyfluorene nanoparticles, along with its utilization in biological oxygen sensing. CPNPs demonstrate exceptional light-absorbing capabilities when contrasted with conventional nanoparticles containing dye, silica, or polymer, leading to absorption cross-sections surpassing 10^{-12} cm^2 (for particles approximately 25 nm in diameter). Fluorescence spectroscopy and time-resolved fluorescence measurements reveal efficient energy transfer from the host polymer to the metalloporphyrin acceptors. This results in a radiant phosphorescence that demonstrates high sensitivity to the concentration of molecular oxygen. The small size, exceptional brightness under both conventional and two-photon excitation, and the ability to emit ratiometrically of the nanoparticle sensor, along with the successful demonstration of single-particle sensing and cellular uptake, underscore the potential of doped CPNPs for precise mapping of local molecular oxygen levels in living cells and tissues. The distinctive characteristics of the nanoparticle sensors such as their diminutive dimensions, remarkable luminosity, and radiometric emission

Scheme 6 Chemical structure of PLA-donor-acceptor coaxial membrane components [54]



combined with the ability to perform single-particle sensing and cellular uptake, underscore their tremendous promise for accurately imaging the local molecular oxygen concentration within living cells and tissues. The study showed the phenomenon of energy-transfer-mediated phosphorescence from obtained nanoparticles and its utility in biological oxygen sensing. Compared to conventional dye-loaded silica or polymer nanoparticles, these conjugated polymer nanoparticles exhibit very good light-harvesting capabilities. Single-particle phosphorescence imaging revealed the sensitivity of phosphorescence intensity to oxygen partial pressure. The nanoparticle sensor's small size, exceptional brightness under both conventional and two-photon excitation, and ratiometric emission, shows the potential of doped semiconducting polymer dots for precisely mapping local molecular oxygen levels in living cells and tissues.

Electrospinning and FONs methods exhibit similar adjustable energy transfer capabilities that enhance luminescence for various applications. Together, these studies highlight the versatility of both methods in controlling energy transfer, advancing lighting technologies, biological imaging, and sensor development.

2.5 Biocompatibility

Recent studies have shown that electrospinning and fluorescent organic nano-dots are suitable for biomedical applications.

Latest study [56] introduces a novel enzyme-based electrochemical biosensor using fluorescent peptide self-assembled nanomaterials for sensitive hydrogen peroxide detection. By incorporating phenylalanine-tryptophan dipeptide (WF-D) into the biosensor, the WF-D nanoparticles provided a biocompatible microenvironment for immobilizing horseradish peroxidase (HRP), which preserved the enzyme's catalytic activity. The electrochemical biosensor demonstrated enhanced electron transfer and sensitivity, with a detection limit of 1.8 μM for hydrogen peroxide. The biocompatibility and excellent electrochemical properties of WF-DNPs highlight their potential for safe and effective biosensor applications, offering significant advantages over conventional electrode materials.

The biocompatibility of both electrospinning and nanoparticle methods is clearly demonstrated through the successful development of composite nanofibers containing fullerene nanoparticles, which hold great potential for bioimaging applications [57]. In this study, poly(L-lactide) (PLLA) nanofibers were fabricated via a simple electrospinning method. The resulting composite nanofibers exhibited uniform morphology with smooth surfaces, and their diameters ranged from 300 to 600 nm. Fullerene nanoparticles were encapsulated within these nanofibers, forming

a core-shell structure, which enhanced their overall stability and performance. Notably, the addition of water-soluble fullerene nanoparticles significantly increased the hydrophilicity of the nanofiber scaffolds, making them more compatible with biological environments. The mechanical properties of the composite nanofibers were also well-suited for tissue-engineering applications, providing an excellent platform for further exploration in biomedical fields. In vitro bioimaging experiments using human liver carcinoma HepG2 cells demonstrated the promising capabilities of these composite nanofibers. The intense red fluorescence emitted by the fullerene nanoparticles, which was clearly visible in the cell nuclei, indicated that the nanoparticles were successfully released from the nanofibers and penetrated the cells. This efficient cellular uptake suggests that the composite nanofibers can be effectively used as scaffolds for bioimaging, confirming their potential for use in drug delivery and other biomedical applications. Furthermore, the use of both electrospinning and nanoparticle methods together in this study highlights the biocompatibility of these techniques. The combination of these methods supports the creation of advanced biomaterials that are not only effective for bioimaging but also demonstrate excellent compatibility with living cells, further establishing their viability in various medical and industrial applications.

2.6 Thermostability Enhancement

As previously mentioned [38, 39], via electrospinning method it is possible to enhance thermal stability. The thermal stability of nanoparticles synthesized through a one-pot procedure, particularly fluorescent mesoporous aluminosilicates, is also notable [58]. These nanoparticles, created from AlO_iPr, tetraethyl orthosilicate (TEOS), and tetraethylammonium hydroxide (TEAOH) precursors in the presence of Rhodamine B, exhibit excellent thermal and chemical stability. When exposed to aqueous acetic acid at 80 °C for 12 h, the nanoparticles maintained their integrity and fluorescence properties after repeated centrifugation and re-dispersion. This resilience is attributed to strong interactions between the chromophore and the inorganic aluminosilicate species, which prevent degradation and preserve the fluorescence capability even under harsh conditions. These interactions result in structural modifications during hydrothermal treatment and contribute to large Stokes shifts in the fluorescence spectra. The nanoparticles also demonstrate enhanced stability with longer emission lifetimes, further confirming their robustness for use in demanding applications.

Table 1 provides a comprehensive summary of all the organoluminophores discussed in the article, including their key photoluminescent properties.

Table 1 Summary of organoluminophores presented in the article

Fluorescent molecules	Nanotechnology	Fluorescent properties	Applications	References
Tetrakis(μ 3-N-(3,5-dichlorosalicylideneamino)ethanolato)-Cu(II)	ES	Electrospun fibers emitted at 522 nm, while complex itself showed a 470 nm emission	Optoelectronics	[37]
• Carbazole based quinoline (P1)	ES	λ_{em} = 478, 525 nm (P1 composite)	Optoelectronics	[38]
• Carbazole based quinoxaline (P2)		λ_{em} = 475, 515 nm (P2 composite)		
• Carbazole based pyrazine (P3)		λ_{em} = 490, 550 nm (P3 composite)		
		Composite nanofibers exhibit red-shifted emission peaks due to CdS-induced bandgap tuning and enhanced charge carrier dynamics		
Rhodamine B@zeolitic imidazolate framework-71	ES	λ_{em} = 550–600 nm Composite fibers exhibit a tunable redshift in emission and a remarkably high quantum yield (up to 92%)	Optoelectronics	[39]
Polyquinoxalin	ES and FONs	λ_{em} = 400–450, 500 nm Fluorophore exhibit concentration- and phase-dependent emission changes	Sensing	[41]
• 5,10,15-tris(4-(4,6-diphe-nyl-1,3,5-triazin-2-yl)phenyl)-10,15-dihydro-5H-diindolo[3,2-a:3',2'-c]carbazole (Ttrz-DI)	FONs	The fluorescent quantum yield (Φ_f) and color conversion efficiency (CCE) of four compounds: Ttrz-DI exhibits a moderate Φ_f of 70% and a CCE of 12.8%, CzDABNA shows a lower Φ_f of 61.8% and a CCE of 4.3%, in contrast, 4tBuMB achieves a perfect Φ_f of 100% and a relatively high CCE of 27.8%, and TNAP also performs well with a high Φ_f of 89.4% and the best CCE among the group at 31.1%	Optoelectronics	[42]
• 2,12-di-tert-butyl-N,N,5,9-tetrakis(4-(tert-butyl)phenyl)-5,9-dihydro-5,9-diaza-13b-boranaphtho[3,2,1-de]anthracen-7-amine (CzDABNA)				
• 1,3,7,9-tetrakis(4-(tert-butyl)phenyl)-5,5-difluoro-10-(2-methoxyphenyl)-5H-4l4,5l4-dipyrrolo[1,2-c:2',1'-f][1,3,2]diazaborinine (4tBuMB)				
• N,N,6,10-tetra(naphthalen-2-yl)-6,10-dihydro-6,10-diaza-16b-boraaanthra[3,2,1-de]tetracen-8-amine (TNAP)				
9,10-distyrylanthracene	FONs		Sensing	[43]
• Poly(9,9-dioctylfluoreny-2,7-diyl) (PFO)	ES	Aggregation-Induced Emission (AIE) property and Φ_f = 40% PFO-dominant fibers emit at 426–445 nm with high photoluminescent (PL) efficiency (up to 48.9%), while MEH-PPV introduces a red-shifted emission at 564 nm, becoming dominant as its content increases. Together, they produce dual or triple emissions with a progressive blue shift in shorter wavelengths and a significant drop in PL efficiency as MEH-PPV content rises	Optoelectronics and sensing	[44]
• Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV)	ES	Random mats containing MEH-PPV exhibit an emission peak at 621 nm and a lifetime of 1.54 ns, while alignment shifts the emission to 604 nm with a lifetime of 1.52 ns. Stretching reduces the emission wavelength to 588 nm, with a slight increase in lifetime (1.92 ns for twice-stretched and 1.76 ns for three-times-stretched fibers)	Optoelectronics	[45]
Quantum dots (QDs)	FONs	The PL properties of QDs—642 nm emission wavelength. Fluorescence intensity is proportional to QD concentration. The QDs' fluorescence intensity is also influenced by the local electric field, where concentration increases in high-field regions following a Boltzmann distribution	Medicine	[46]
• Imidazole-based units (P1—with methoxy groups, P3—with oligoethylenecoxy groups)	FONs	P1 and P3 exhibiting a broad emission tail reaching into the near-IR with emission maxima around 670 nm. P2 shows a blue-shifted emission maximum at 630 nm. P4 has an emission maximum at 570 nm	Medicine	[47]
• p-diiodobenzene-based units (P2—with methoxy groups, P4—with oligoethylenecoxy groups)				

Table 1 (continued)

Fluorescent molecules	Nanotechnology	Fluorescent properties	Applications	References
1-cyano-trans-1,2-bis-(4'-methylbiphenyl)-ethylene	FONs	The fluorescence intensity is 700 times higher at 80% water fraction, due to nanoparticle formation	Sensing	[48]
2,3-bis(4-(10H-phenoxazin-10-yl)phenyl)-6-(10H-phenoxazin-10-yl)-quinoxaline (DBQ-3PXZ)	FONs	DBQ-3PXZ shows an emission shift from 660 nm in Tetrahydrofuran solution to 585 nm in NPs, with a quantum yield of 3.8% and intensity 27 times higher. The fluorescence lifetime is 2.7 ns, compared to 1.38 ns in argon-purged toluene, due to AIE effects	Medicine	[50]
• MEH-PPV • Poly(3-hexylthiophene) (P3HT)	ES	MEH-PPV/PEO nanofibers show red-shifted emission (590 nm) vs. dilute solution (550 nm), due to aggregation. Lower MEH-PPV ratios reduce aggregation, blue-shifting the emission. P3HT/PEO nanofibers are red-shifted by 70–80 nm from solution, reflecting strong π - π stacking	Optoelectronics	[51]
• 1,8-naphthalic anhydride (B) • Perylene mono-anhydride (O)	ES	B (blue emission donor) and O (orange emission acceptor) dyes, when mixed, exhibited white emission both in solution and in the fibrous membrane state	Optoelectronics	[54]
• Poly(9,9-dihexylfluorene) (PDHF) • Poly(9,9-dioctylfluorene) (PFO) • Platinum (II) octaethylporphine (PtOEP)	FONs	PtOEP-doped FONs exhibit oxygen-sensitive red phosphorescence (650 nm), which decreases under air or oxygen saturation, while donor fluorescence (420 nm) remains constant	Medicine and sensing	[55]
Phenylalanine-tryptophan dipeptide (WF-D)	FONs	WF-D FONs displayed fluorescence with peaks under 280 nm and 370 nm excitation. Fluorescence quenching occurred when mixed with graphene oxide (GO) or citrate-modified gold nanorods (AuNRs), with intensity changes observed at 428 nm. The quenching effect varied with the concentration of GO or AuNRs, and WF-D FONs exhibited good fluorescence stability, even in the presence of AuNRs	Medicine and Sensing	[56]
Fullerene	ES and FONs	The PL of fullerene derivatives showed maximum emission wavelengths at 550–575 nm. Nanofibers encapsulating fullerene nanoparticles showed characteristic PL emissions, confirming successful incorporation. The encapsulation caused a blue shift and reduced fluorescence efficiency compared to fullerene solutions	Medicine	[57]
Rhodamine B (RhB)	FONs	RhB-loaded nanoparticles exhibited a blue-shifted emission peak at 577 nm (vs. 592 nm in solution) and an increased fluorescence lifetime of 3.9 ns (vs. 1.6 ns in solution)	Diverse applications	[58]

3 Discussion

Based on the literature review described earlier, electrospinning emerges as a distinctive method for nanomaterial production, particularly in the utilization of organic fluorophores. Its versatility is evidenced by the ability to produce fibers from a wide range of materials, including polymers, composites, and their combinations with inorganic compounds. Furthermore, electrospun fibers exhibit enhanced luminescence efficiency and a broader range of emitted colors compared to other methods. These advantages, coupled with the capability to produce heat-resistant fibers, make ES exceptionally well-suited for optoelectronic applications. Notably, electrospinning allows precise orientation control of macromolecular chains inside nanofibers, thereby influencing their optical properties. Modern approaches such as coaxial electrospinning highlight ES's capacity to regulate energy transfer, particularly in semiconducting materials. Additionally, the elasticity of nanofibers and the ability to increase photoluminescent polarization further enhance the utility of electrospinning in optoelectronic devices.

The advantages of this method do not end there. Properties such as fiber diameter, morphology, and porosity are easily controllable by adjusting parameters like polymer concentration, solvent type, and processing conditions, what makes ES suitable for any kind of luminescent materials. Electrospinning can be readily scaled up for industrial production and being a continuous operation with solvent-based process, using environmentally friendly solvents, generates minimal waste, facilitating large-scale manufacturing.

However, there are several issues with upscaling the process of ES. Multi-needle electrospinning, an extension of the single-needle method for industrial utilizing, boosts nanofiber production with varying properties, yet faces challenges in needle interaction and clogging. Different needle arrangements, including concentric heads, have been explored to improve efficiency. Higher voltage is needed due to the larger solution mass, with rotating spinnerets reducing clogging risk by employing centrifugal force. Despite advancements, system complexity limits widespread adoption [59, 60]. Needleless electrospinning was devised to address limitations of needle-based methods, offering benefits like increased production rates and scalability, with reduced clogging risks. However, it demands high voltage to overcome surface tension and faces challenges in maintaining solution viscosity [61]. Nevertheless, scientists are constantly achieving the scalability of ES process conducting different approaches. Recent studies demonstrate that many companies manufacturing ES equipment now provide solutions for a scalable nanofibers production [62].

Electrospinning often relies on volatile organic solvents like tetrahydrofuran, dichloromethane, chloroform, and

N,N-dimethylformamide which pose environmental and health risks due to their toxicity and vapor emissions. These solvents also increase production costs and may limit application scope due to residual traces [63]. To mitigate these issues, alternative methods such as melt electrospinning [64], the use of “green” solvents like deep eutectic solvents and biodegradable polymer suspensions [65], and solvent-free techniques like wire melt electrospinning [66] have been developed. These innovations enhance the sustainability and economic feasibility of the electrospinning process.

Fluorescent organic nano-dots, in turn, are characterized by their ability to create biodegradable conjugated polymer particles with enhanced optical properties due to dense packing of the luminophore. They also have the capability to improve energy transfer efficiency, which proves useful in sensing technology. Similar to electrospinning, FONs method significantly enhances light emission, enabling the detection of organic vapors. Notably, they are easy to prepare and do not require special equipment, making them environmentally friendly. Additionally, they exhibit excellent optical characteristics and biocompatibility. Moreover, FONs exhibit enhanced brightness and exceptional photostability, along with an extremely long lifespan of luminescence.

The scalability of FONs production is still under development; however, there are already several methods that show promise for industrial utilization [67, 68].

Fluorescent organic nano-dots derived from traditional organic dyes typically exhibit several issues. These include the well-known aggregation-caused quenching (ACQ) effect [69] and a lack of stability in physiological solutions. One approach to address these challenges is through AIE dyes, which can circumvent the ACQ effect. However, synthesizing AIE dyes is complex, time-intensive, and expensive [19]. The issue with ACQ can be overcome through the ES method, which is definitely a significant advancement over the FONs method [70].

Research on organic dye nanoparticles is still in its early stages, and considerable work needs to be done before they can be developed further. For instance, creating techniques to create organic dye nanoparticles with the appropriate shapes, sizes, and structures remain a crucial task. In fact, it is still challenging to create organic dye nanoparticles that are as small as inorganic ones—less than 10 nm in diameter. The performance and endurance of organic dyes are greatly influenced by their thermal stability, which varies greatly based on their molecular structure and class. Given that dyes with near-infrared (NIR) wavelengths are frequently more prone to thermal degradation because of their intricate electronic structures and lengthy conjugation systems, this factor is particularly important. Long-term use or high temperatures can cause NIR dyes to undergo increased thermal stress, which can result in color shifting, a reduction

Table 2 Comparison of electrospinning and fluorescent organic nanodots methods based on their advantages and disadvantages

Advantages & disadvantages	ES	FONs
Versatility in used materials	[37–39, 41]	[42, 43]
Luminescent properties and emission dynamics enhancement	[44, 45]	[46–50]
Orientation control of macromolecular chains	[51]	-
Adjustable energy transfer capabilities	[54]	[49]
Biocompatibility	[57]	[56, 57]
Thermostability enhancement	[38, 39]	[58]
Scalability	[62]	[67, 68]
Aggregation-caused quenching	-	[69]
Downscaling	[74]	-

in fluorescence efficiency, or possibly the dye molecules breaking down entirely.

When evaluating the durability and effectiveness of organic dyes, photochemical stability is an important consideration, particularly when the dyes are exposed to light for prolonged periods of time. Many visible-spectrum dyes offer adequate photochemical stability for common applications like common display technologies or fluorescence microscopy. These dyes provide steady performance over time because they can withstand moderate light levels without suffering appreciable deterioration. High light flux conditions, on the other hand, present challenges because intense or continuous illumination can accelerate photodegradation. Near-infrared (NIR) wavelength dyes are especially susceptible to breakdown under intense light sources because of their complex molecular structures and lower photon energies, which makes them less photostable. This issue is made even more dire. Shorter operational lifespans, spectral shifts, and decreased fluorescence intensity can result from this. Therefore, increasing the photochemical stability of NIR dyes is crucial for demanding applications like photodynamic therapy, laser technologies, and high-intensity imaging. In order to maintain dye performance under difficult lighting conditions, strategies to improve stability include protective encapsulation, hybrid material development, and molecular modifications [24, 71].

Nanoparticles of conjugated polymers possess hydrophobic properties; therefore, they are rapidly absorbed by cells and exhibit low cytotoxicity, making them possible to use for bio-imaging due to their strong fluorescence [72]. There is also a problem in biological utilization of FONs, because clinical nanoparticles must be small (5–6 nm) to clear through renal purification. Small particles address accumulation issues but often lack sufficient fluorescence, limiting the safe use of conjugated polymer particle systems in vivo [47, 73]. Unlike FONs, the electrospinning method allows for size reduction, which can be achieved by

utilizing techniques like microfluidics-based spinning [74]. This method enables the production of submicron-thick “noodle-like” fibers, overcoming limitations in pore size and fiber scaling. Additionally, electrospinning allows for the creation of freestanding porous membranes with more controlled pore sizes, making it highly beneficial for applications in tissue engineering, drug delivery, and organ-on-a-chip research.

All advantages and disadvantages of both methods are collected in Table 2.

4 Conclusion

In conclusion, electrospinning and fluorescent organic nanodots (FONs) represent advanced methods for nanomaterial production, each offering unique advantages and addressing specific challenges in their respective fields.

Electrospinning distinguishes itself through its remarkable versatility, capable of processing diverse materials such as polymers, composites, and hybrid organic–inorganic systems. This method excels in tailoring nanofiber properties, including morphology, porosity, and luminescent behavior, by adjusting parameters like polymer concentration and solvent choice. Its ability to enhance luminescence efficiency, control energy transfer, and achieve precise macromolecular chain orientation makes it highly suitable for optoelectronic applications. Additionally, scalability advancements, such as needleless and multi-needle setups, have positioned electrospinning as a promising tool for industrial production. Despite these strengths, challenges persist, including clogging in multi-needle systems, high-voltage requirements, and complexity in large-scale operations.

In contrast, FONs offer significant promise for bio-imaging and sensing technologies due to their biocompatibility, brightness, exceptional photostability, and environmentally friendly synthesis processes. The compact nature of FONs enhances their optical properties, enabling high-sensitivity applications such as organic vapor detection. However, limitations include the aggregation-caused quenching (ACQ) effect and difficulties in maintaining stability in physiological conditions. While AIE dyes address the ACQ issue, their synthesis remains complex and costly. Furthermore, the production scalability of FONs is still under development, and the small size required for clinical applications often compromises fluorescence intensity, restricting their in vivo utility.

Interestingly, electrospinning can complement FONs by mitigating some of their drawbacks. For example, ES can address ACQ by dispersing luminophores in nanofibers and enabling the production of size-controlled materials with improved fluorescence [75]. The creation of submicron-thick

fibers and porous membranes extends the applicability of electrospinning to areas such as tissue engineering, drug delivery, and organ-on-a-chip research [76, 77].

Electrospun fibers demonstrate superior luminescence efficiency compared to fluorescent organic nanoparticles (FONs), as evidenced by their enhanced photoluminescent properties and emission dynamics. This efficiency is attributed to the fine-tuned polymer compositions and the formation of smaller polymer domains during the electrospinning process, which facilitate more effective energy transfer and reduce non-radiative energy losses. The resulting nanofibers display a broader range of emission colors and stronger fluorescence. These attributes position electrospun fibers as a highly versatile and efficient platform for applications in optoelectronics, advanced light sources, and sensory materials. In contrast, while FONs offer advantages like tunable fluorescence and biocompatibility, their luminescent efficiency is generally lower, making them more suitable for specific applications like biomedical imaging and drug delivery rather than high-performance light-emitting devices.

In summary, while electrospinning is particularly advantageous for applications requiring material scalability, enhanced luminescence, and structural customization, FONs excel in bio-imaging due to their optical properties and biocompatibility. Each method has distinct strengths and limitations, highlighting the importance of tailoring the approach to specific application requirements. These complementary technologies hold immense potential for advancing fields such as optoelectronics, biomedical imaging, and sensing.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

Ethical Approval This study does not involve any primary data collection or experimentation with human or animal subjects.

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