

UNIVERSIDAD DE INVESTIGACION DE TECNOLOGÍA EXPERIMENYAL YACHAY

Escuela de ciencias Físicas y Nanotecnología

Luminescent polymers

Trabajo de integración curricular presentado como requisito para la obtención del título de ingeniero en Nanotecnología

Autor:

Paul Eduardo Freire Obando

Tutor:

Gema González Vazquez

Co-tutor:

Antonio Díaz Barrios

Urcuquí, septiembre 2022



Urcuquí, 5 de septiembre de 2022

SECRETARÍA GENERAL ESCUELA DE CIENCIAS FÍSICAS Y NANOTECNOLOGÍA CARRERA DE NANOTECNOLOGÍA ACTA DE DEFENSA No. UITEY-PHY-2022-00019-AD

En la ciudad de San Miguel de Urcuquí, Provincia de Imbabura, a los 5 días del mes de septiembre de 2022, a las 16:00 horas, en el Aula S_CAN de la Universidad de Investigación de Tecnología Experimental Yachay y ante el Tribunal Calificador, integrado por los docentes:

Presidente Tribunal de Defensa	Dr. LOBOS MARTIN, JUAN, Ph.D.	
Miembro No Tutor	Dr. CAETANO SOUSA MANUEL, Ph.D.	
Tutor	Dra. GONZALEZ VAZQUEZ, GEMA, Ph.D.	

Se presenta el(la) señor(ita) estudiante FREIRE OBANDO, PAUL EDUARDO, con cédula de identidad No. 1715142665, de la ESCUELA DE CIENCIAS FÍSICAS Y NANOTECNOLOGÍA, de la Carrera de NANOTECNOLOGÍA, aprobada por el Consejo de Educación Superior (CES), mediante Resolución RPC-SO-13-No.156-2015, con el objeto de rendir la sustentación de su trabajo de titulación denominado: LUMINESCENT POLYMERS, previa a la obtención del título de INGENIERO/A EN NANOTECNOLOGÍA

El citado trabajo de titulación, fue debidamente aprobado por el(los) docente(s):

Tutor	Dra. GONZALEZ VAZQUEZ, GEMA, Ph.D.	
Co - Tutor	Dr. DIAZ BARRIOS, ANTONIO, Ph.D.	

Y recibió las observaciones de los otros miembros del Tribunal Calificador, las mismas que han sido incorporadas por el(la) estudiante.

Previamente cumplidos los requisitos legales y reglamentarios, el trabajo de titulación fue sustentado por el(la) estudiante y examinado por los miembros del Tribunal Calificador. Escuchada la sustentación del trabajo de titulación, que integró la exposición de el(la) estudiante sobre el contenido de la misma y las preguntas formuladas por los miembros del Tribunal, se califica la sustentación del trabajo de titulación con las siguientes calificaciones:

Tipo	Docente	Calificación
Presidente Tribunal De Defensa	Dr. LOBOS MARTIN, JUAN, Ph.D.	9,1
Tutor	Dra. GONZALEZ VAZQUEZ, GEMA, Ph.D.	9,5
Miembro Tribunal De Defensa	Dr. CAETANO SOUSA MANUEL, Ph.D.	9,5

Lo que da un promedio de: 9.4 (Nueve punto Cuatro), sobre 10 (diez), equivalente a: APROBADO

Para constangia de lo actuado, firman los miembros del Tribunal Calificador, el/la estudiante y el/la secretario ad-hoc.

FREIRE OB DO, PAUL EDUARDO Estudiante Dr. LOBOS MARTIN, JUAN, Ph.D. Presidente T de Defensa

Dra. GONZALEZ VAZQUEZ, GEMA, Ph.D. Tutor

Dr. CAETANO SOUSA MANUEL , Ph.D. Miembro No Tutor



trange (

CIFUENTES TAFUR, EVELYN CAROLINA Secretario Ad-hoc

AUTORÍA

Yo, **Paul Eduardo Freire Obando**, con cédula de identidad 1715142665, declaro que las ideas, juicios, valoraciones, interpretaciones, consultas bibliográficas, definiciones y conceptualizaciones expuestas en el presente trabajo; así cómo, los procedimientos y herramientas utilizadas en la investigación, son de absoluta responsabilidad de el/la autora (a) del trabajo de integración curricular. Así mismo, me acojo a los reglamentos internos de la Universidad de Investigación de Tecnología Experimental Yachay.

Urcuquí, septiembre 2022.

Paul Eduardo Freire Obando CI: 1715142665

AUTORIZACIÓN DE PUBLICACIÓN

Yo, **Paul Eduardo Freire Obando**, con cédula de identidad 1715142665, cedo a la Universidad de Investigación de Tecnología Experimental Yachay, los derechos de publicación de la presente obra, sin que deba haber un reconocimiento económico por este concepto. Declaro además que el texto del presente trabajo de titulación no podrá ser cedido a ninguna empresa editorial para su publicación u otros fines, sin contar previamente con la autorización escrita de la Universidad.

Asimismo, autorizo a la Universidad que realice la digitalización y publicación de este trabajo de integración curricular en el repositorio virtual, de conformidad a lo dispuesto en el Art. 144 de la Ley Orgánica de Educación Superior

Urcuquí, septiembre 2022.

Paul Eduardo Freire Obando CI: 1715142665

Acknowledgements

First of all, I would like to thank God for giving me the strength, wisdom and patience to accomplish successfully my goal in this unforgettable part of my life that was university. Further I would like to give special thanks to my thesis advisor Gema González, for the enormous patience that she gave me in the different difficulties that I encountered along the way, and with her support and understanding, she knew how to motivate me to continue progressing in the development of my thesis. I would also like to express my gratitude to Yachay Tech University and all the professors that taught me all the knowledge and skills that I have applied in this journey. To con conclude, I want to thank my family specially my mother and my brother for being my source of inspiration and strength whom I see as the meaning of resilience. I also cannot forget to thank my friends who supported as a second family, which I had the opportunity to live unique hard and happy moments with them through these years.

Abstract

Polymers are well known and widely used materials that are made of repetitive small molecules called monomer. Their characteristics and properties are particular, depending on the kind of monomers that are bonded and also the way they are linked to each other. Polymer's presence is very wide in contemporary life, because there is a great variety of them, and one the main classifications of polymers is based on natural and synthetic polymers [1]. On the other side, luminescence is the emission of light waves that produce some bodies when they are at moderate temperatures, then that it is not consequence of heat exposition, that is the reason that kind of light emission is called cold light[2].

The present work is an extensive review of all the phenomena that are associated with the luminescence that some polymers present such as: The review start with de phenomena of luminescence by itself, then the classification of luminescent polymers with several kinds of polymers it is going to be presented. Also it is going to be review the importance of luminescent polymers and their broad range of applications. This includes which kind of polymers have been used in different fields, from the well know organic-emitting light diodes (OLEDS) used in screens for the develop of electronic devices, to applications in energy industries by solar cells, and also in the field of medicine by bioimaging applications[3]. And finally, it will be revised the aggregation induced luminescence or aggregation-induced emission (AIE) and why these phenomena occur in some materials.

The objective of this review is to develop a wide and general overview that of the types of luminescent polymers applications, the reasons of the occurring phenomena and also why they can become important in different fields and applications.

Keywords: Polymers, luminescence, applications

<u>Resumen</u>

Los polímeros son materiales bien conocidos y ampliamente utilizados que están hechos de repetitivas de pequeñas moléculas denominadas monómeros. Sus características y propiedades son particulares, dependiendo del tipo de monómeros que están unidos y también de la forma en que se unen entre sí. La presencia de los polímeros es muy amplia en la vida contemporánea, porque existe una gran variedad de ellos, y una de las principal clasificaciones de polímeros de polímeros se basa en polímeros de origen natural y polímeros sintéticos [1]. Por otro lado, el fenómeno de luminiscencia, consiste es la emisión de ondas de luz que producen unos cuerpos que se encuentran a temperaturas moderadas, lo cual significa que no es consecuencia del calor y esta es la razón por la que ese tipo de emisión de luz se llama luz fría [2].

En este trabajo se hace una revisión extensa y detallada de los fenómenos que se asocian a la luminiscencia que presentan algunos polímeros tales como: La luminiscencia inducida por agregación o emisión inducida por agregación (AIE) y por qué estos fenómenos ocurren en algunos materiales. También se mencionan y revisas la importancia de los polímeros luminiscentes en un amplio abanico de aplicaciones, en las que este tipo de polímeros se han utilizado en diferentes campos, desde los conocidos diodos LED emisores orgánicos (OLED) utilizados en pantallas para el desarrollo de dispositivos electrónicos, hasta aplicaciones en industrias energéticas mediante células solares, y también en el campo de la medicina mediante aplicaciones de bioimagen [3].

El objetivo de este artículo de revisión es desarrollar una visión amplia y general de los tipos de aplicaciones de polímeros luminiscentes, las razones de los fenómenos que ocurren y también por qué pueden llegar a ser importantes en diferentes campos y aplicaciones.

Palabras clave: Polímeros, luminiscencia, aplicaciones

Contents

1	In	trodu	iction1				
	1.1	Bri	ef history of Polymers1				
	1.2	Obj	jectives2				
	1.2	2.1	General2				
	1.	2.2	Specific2				
2	Tł	heoret	ical background3				
	2.1	Lui	ninescence3				
	2.2	1.1	Types - Categories of luminescence4				
3	Re	eview	of luminescent polymers15				
	3.1	Luı	ninescence in conjugated polymers15				
	3.	1.1	Conjugated polymers15				
	3.	1.2	Conjugated luminescent polymers15				
	3.	1.3	Examples of luminescent conjugated polymers17				
	3.2	Lui	ninescence in non-conjugated polymers19				
	3.2	2.1	Non-conjugated luminescent polymers19				
	3.2	2.2	Examples of non-conjugated luminescent polymers20				
	3.3	Luı	ninescence in polymers with hydrogen bonding21				
	3.	3.1	Hydrogen bonding in polymers21				
3.3.2		3.2	Examples of luminescence in hydrogen bonding22				
	3.4 Composite and hybrid luminescent polymers		nposite and hybrid luminescent polymers23				
3.4.1 Luminescent Polymers with nanoparticles (composites)		Luminescent Polymers with nanoparticles (composites)24					
	3.4	4.2	Hybrid luminescent polymers				
	3.5	Сог	ventional luminescent polymers26				
	3.6	Noi	n-conventional luminescent polymers26				
	3.7	Me	chanisms27				
	3.	7.1	Mechanisms of luminescence in polymers27				
	3.8	Ap	plications of luminescent polymers34				
	3.8	8.1	Organic light emitting diodes (OLEDs)				
	3.8	8.2	Luminescent polymers for bioimage				
4	Di	Discussion40					
5	Co	Conclusion41					

List of figures

Figure 1. Monomer and polymer general structures

Figure 2. Simplified Jablonski diagram of the energy levels.

Figure 3. A summary of the several categories of light emission. Taken from reference

Figure 4. Diagram showing the difference between fluorescence and phosphorescence.

Figure 5. Basic electroluminescent diagram structure.

Figure 6. Example of an electroluminescent flexible textile gadget

Figure 7. a) Cathodoluminescent imaging obtained by a Scanning electron microscope (SEM), left. b) True color imaging using an optical CL microscope.

Figure 8. Example of radioluminescence imaging in a microscope

Figure 9. In vivo imaging of luminescent particles detected by radioluminescence.

Figure 10. Examples of marine bioluminescence.

Figure 11. Example of chemiluminescence. A glowing stick.

Figure 12. Triboluminescence application illustration

Figure 13. SEM picture of sonochemically produced haemoglobin protein microspheres

Figure 14. Examples of polymers and oligomers presented in the first studies of luminescence of polymers.

Figure 15. Boron quinolate chemical structure

Figure 16. Aluminum quinolate chemical structure

Figure 17. Boron diketonate chemical structure

Figure 18. Figure 18. Boron dipyrromethene chemical structure

Figure 19. Pyrazabole chemical structure

Figure 20. Image of chitosan fiber mesh

Figure 21. Hydrogen bonding representation of phenol multimer

Figure 22. Example of hydrogen bonding.

Figure 23. ACQ effect in a solution/suspension of DDPD

Figure 24. Representation of ACQ effect.

Figure 25. Representation of AI effect

Figure 26. Aggregation's effect on the luminescence behavior of a polymer

Figure 27. OLED passive matrix representation.

Figure 28. OLED passive matrix representation

Figure 29. White OLEDs

Figure 30. Representation of fluorescent polymers for bioimaging

List of tables

Table 1. Comparative table of examples of non-conjugated luminescent polymers

1 Introduction

1.1 Brief history of Polymers

The term "polymer" was popularized by the Swedish scientist J. Berzelius, it appeared in the 1920s. Polymer science is nearly a novel field of study and investigation which has a lot to do with different kinds of materials that could be natural or synthetic. All these goods seem to be very familiar in everyday life[4].

There are different purposes that the different kinds of polymers that can be used. For instance, on type of polymers called plastics whose main characteristic is to be produced in very high volume and low price, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and in the other hand, there could be more specific engineered plastics that can have a higher cost and low volume of production. Also, there are different kinds of polymers transformed into fibers that can be natural or synthetic and their main characteristic is to having high strength and high aspect ratio based on the use that they could have[4]. Another kinds of polymers that exist are the elastomers, which can have the characteristic of being elastic, this with the capability to be extended when a force is applied and return fast to its normal form once this force is retired. All these different kinds of polymers can be used for specific tasks and applications.

By their use, the different kind of polymers that can be used daily, are classified as plastics, fibers and elastomers or rubbers. First plastics developed were based on nitrocellulose and was obtained by Parkes in 1862, then the material camphor was combined with nitrocellulose and that gave rise to the first approximation to a thermoplastic, which is a substance that can soften or melt when it is heated and then harden again when temperature drops. One example of the use of this polymer was for cinema films. Then fibers, which their main aspect is that they have a filament shape. There are fibers based on different materials which could be made of mineral, metallic or organic materials, but also the nonmetallic fibers that can be organic or inorganic[4]. And lastly, there are the elastomers or rubbers, which are a kind of polymers that can possess the properties of viscosity and also elasticity, so it has a rubber-like nature[5].



In figure 1, it is graphically explained that a polymer is constructed by a conjunction of several monomers. In between all the types of polymers that could be found in nature or also be manmade, there exist luminescent polymers that can present different singular applications and novelties. Firstly, in order to understand about the characteristics and applications presented by luminescent polymers, an introduction to the phenomenon of luminescence is presented below.

1.2 Objectives

1.2.1 General

- Present a literature review on luminescent polymers by using various search sources for scientific papers, including scientific journals and repositories, and search engines like Scholar Google, and Scopus, to compile a comprehensive review of luminescence in polymers.

1.2.2 Specific

- Contrast different research studies about luminescent polymers.

2 Theoretical background

2.1 Luminescence

Luminescence may be thought of as the process by which excited state electrons shift between energy levels, as shown in figure 2 by the Jablonski diagram. Numerous significant transitions are identified, including absorption, internal conversion, and intersystem crossover.

Additionally, two broad relaxation paths are illustrated: radiative decay through luminescence (fluorescence occurs when the electron moves from S_n to S_0 , while phosphorescence happens when the electron moves from T_n to S_0). The other relaxation path is non-radiative decay without luminescence.[6] The intrinsic process of the two primary types of photoluminescence, fluorescence, and phosphorescence, may be succinctly illustrated using a Jablonski diagram, using arrows indicating probable electron transitions. Fluorescence is the emission of a single excited state that occurs due to light absorption. Phosphorescence is the emission of a triplet state from the singlet excited state S_1 , to the triplet excited state T_1 . after an intersystem crossover.[7]



Figure 2. Simplified Jablonski diagram of the energy levels. Taken from reference. [7]

Luminescence is a process in which a substance absorbs energy from an external source and re-emits it as visible light. Luminescence sometimes referred to as "cold light" is the spontaneous emission of light by an unheated material. As a consequence, it is a sort of cold-body radiation that may be generated as a result of a variety of interactions, including chemical processes, electrical energy, and even crystal stress. One characteristic of Luminescence that is going to be mentioned ahead is that the difference from incandescence by the fact that incandescence occurs when a material is heated.[2]. In figure 3, it is explained about the different types and categories of luminescence that exist, some types of luminescence as mentioned before, can present different properties for instance, at presenting heat in the process of emission, as well as mechanical forces, light excitation or even motion.[8]



2.1.1 Types - Categories of luminescence.

Figure 3. A summary of the several categories of light emission. Taken from reference [8].

2.1.1.1 Photoluminescence

In order for a material present photoluminescence (PL), it is needed that the material first takes in photons which is represented as electromagnetic radiation, and after that light is going to be emitted from the material. The main characteristic of this type of luminescence is that the incoming photons are going to energize the electrons of the material to a superior level in the atom.

There are sub-types of photoluminescence which are fluorescence and phosphorescence. First fluorescence happens when an electron absorbs energy from light, this means that it absorbs a photon of light, then after this absorption, an excited electron jumps up an energy level and then after that, the electron falls back down to the original level, resulting in the emanation of a photon of light[9]. It is important to notice that light in fluorescence is not permanent, so when there is no applied light there will not be emitted light. For example, there are fluorescent minerals such as calcite.[10] Phosphorescence is the phenomenon that some materials present, the characteristic of materials that present phosphorescence is that they can absorb energy and store it, and after that energy can be emitted as radiation[3]. This process is related to fluorescence, but the difference here is that the material here, can store light energy and the electrons emit photons for a longer period of time. A very well-known example here is phosphorescent paint or glow-in-the-dark paint.[11]

There is a difference between fluorescence and phosphorescence and it is that in fluorescence, the excited electrons instantly emit photons of light, and after that, it returns to their initial energy level, and as mentioned before, if there is no applied a source of light, there will not be more light emitted. On the other hand, the phosphorescence excited electrons do not instantly emit photons, but that process happens in a period of several seconds or even hours (Figure 4).[12]



Figure 4. Diagram showing the difference between fluorescence and phosphorescence. Taken from reference .[12]

2.1.1.2 Thermoluminescence

It is another form of luminescence that happens when a substance absorbs and stores energy when exposed to ionizing radiation in preparation for a future discharge in the visible light mode when the material is heated. This kind of luminescence occurs in semiconductors and insulators. Three components must exist in order for thermoluminescence to occur. As previously stated, the studied material must be an insulator or a semiconductor; moreover, the substance must be located near an incising radiation source in order to collect energy. Finally, it must be heated in order to exhibit the luminescence.[13]

Thermoluminescence can occur in some crystalline materials, for instance, such as calcium fluoride, lithium fluoride, calcium sulfate, lithium borate, calcium borate, potassium bromide, fluorite, and finally feldspar.[14]

2.1.1.3 Electroluminescence

When a potential difference is applied over a phosphor material, electroluminescence (EL) occurs. In addition to this concept is that electroluminescence happens when there is an introduction of electrons into the phosphor material therefore this creates free charge carriers and this is called induced luminescence^[15]. Electroluminescent materials emit light when an electric current or strong electric field is applied to them. Electroluminescence is a common phenomenon used in different uses, for instance, in rigid electronic applications and flexible fiber structures. The basic structure of an electroluminescent Therefore, material is made of several layers. electroluminescence structures typically consist of four layers, as shown in figure 5 below. As it is displayed, there are two organic or two inorganic electroluminescent materials, one of which emits electrons and the other of which emits holes. There are two electrodes, and at least one of the electrodes must be transparent, it can be made of, for instance: indium tin oxide (ITO) mounted on glass or plastic is widely used as a top electrode for electroluminescent panels due to its excellent conduction of the electrons and high clearness. The other electrode that is concealed is often made of reflective metallic material. The whole structure is then attached to a support layer customized for the intended use. Supports can be rigid or flexible, but a textile material is beneficial. When the structure receives electrical energy from a power source, the cathode emits electrons, and the anode emits electron holes. The radiative recombination of an electron and an electron-hole release their energy through an exciton emission, resulting in light emission.

The monochromatic light emission leads this exciton to revert to its excitation ground state. The emission spectrum generated is dependent on the electroluminescent material employed. For instance, poly(2-methoxy-5-(20-ethyl-hexoxy)-p-phenylenevinylene) may emit an orange-red hue; poly(p-phenylene vinylene) emits green and polyfluorenes emit blue. Filters can be used to alter the color of an image inside the structure. The brightness of the electroluminescent structure increases linearly with the applied voltage until it reaches its limit. Electroluminescent devices utilze a voltage range of 100–1000 volts (figure 6) .[16]



Figure 5. Basic electroluminescent diagram structure. Taken from reference [16]

Electroluminescence can be exhibited at organic light- emitting diodes (OLEDS). Another example where electroluminescence can be found is in optical fibers.



Figure 6. Example of an electroluminescent flexible textile gadget.[16]

2.1.1.4 Cathodoluminescence

This kind of luminescence has to do with an excitation that occurs to electrons or ion beams, which can also be called ionoluminiscence. Cathodoluminescence (CL) can also be known as the contrary mechanism in the photoelectric effect. An example of cathodoluminescence is using the out-of-date cathode-ray televisions[17].

The fundamental notion of cathodoluminescence is light or electromagnetic radiation in the ultraviolet to the near-infrared range of the electromagnetic spectrum produced by rapid electrons (cathode rays) in an electron beam. One of the most popular applications of cathodoluminescence is in a scanning electron microscope as shown in figure 7. A laser beam is focused on the sample in a vacuum environment holding the material of interest.[18]

Cathodoluminescence may be used to explore subjects such as light propagation, dispersion, the electrical composition of a material, and resonant processes. Consequently, it is a key source of information for both basic and research work, as well as having a real relationship to industry.[19]



Figure 7. a) Cathodoluminescent imaging obtained by a Scanning electron microscope (SEM), left. b) True color imaging using an optical CL microscope. The micrographs illustrate quartz crystals embedded in intricate interior textures of volcanic rocks. Taken from reference [18]

2.1.1.5 Radioluminescence

It derives from synergy among ionizing radiation and matter. It is known that the mentioned radiation can be, for instance, α or β particles. Also, it could be rays such as X-rays or γ rays, or even cosmic rays or photons. Objects that can present radioluminescence are labeled as scintillators, a flare of luminosity that happens when a radiation source hits a metal surface[20].

Different frequency bands within the electromagnetic spectrum are essential for health imaging and treatment. Short frequencies of radioactivity (ionizing radiation) are frequently utilized in radiological and radiological imaging and cancer radiation treatment. Middle frequencies (optical radiation) are advantageous for imaging and photodynamic treatment at a more local or regional scale. Furthermore, magnetic resonance imaging and hyperthermia therapy often use longer wavelengths. There has been a recent rise in research on novel biological approaches that combine optical and irradiation by utilizing ionizing radiation's capacity to induce optical signals. These phenomena collectively referred to as radioluminescence, are exploited in various applications, including radiological imaging, radiation treatment control, photodynamic therapy, and molecular imaging using nanoparticles. One example is shown in figure 8.[21]

For instance, some examples of where radioluminescence can be applied. To begin, radioluminescence microscopy (RLM) is an imaging method.



Figure 8. Example of radioluminescence imaging in a microscope. Taken from reference [21]

In another application where to see the application of radioluminescence is for preclinical imaging, and in vivo activation, persistent luminous nanoparticles based on silicate and polymer have been created. They possess features that make them well-suited for sensitive in vivo imaging.



Figure 9. In vivo imaging of luminescent particles. Taken from reference [21]

2.1.1.6 Bioluminescence

It is a kind of chemiluminescence, but a living organism produces the interaction chemicals, and the light is produced by a chemical reaction occurring inside the organism. Several light-emitting compounds are found in some organisms, but one example is luciferin, which can be found in some bugs such as the firefly.[22]

No parasitic luminous species often includes the gene for its luciferase or photoprotein, if not for the light-emitting luciferin itself. Counting the number of times bioluminescence evolved independently is difficult, and there is a danger of exaggerating or underestimating the number. While bacterial symbiont organisms evolved just once, each squid or fish species that utilize bioluminescence, must acquire special light organs to contain and support the population. Bioluminescent illumination is created when energy is released during a chemical reaction. The oxidation of a light-emitting chemical often commences this luciferin reaction. The luciferin process is sped up by an enzyme, either luciferase or a photoprotein, a kind of luciferase in which the components required for light emission are covalently bonded together. Photoproteins create light when they bind another ion, for instance, Ca_{2+} or Mg_{2+} , altering the structure of the protein. This technique allows the organism to precisely control the emission of light. While several kinds of luciferins account for the majority of light generated in the water, there are certainly countless other light-emitting activities. In figure 10 there is different examples of bioluminescence found underwater.[23]



Figure 10. Examples of marine bioluminescence. Taken from reference [23]

2.1.1.7 Chemiluminescence

Chemiluminescence arises when electrons are activated by chemical processes rather than light energy, as with other types of luminescence. Thus, the chemical events occurring are oxidation-reduction reactions, as seen in manufactured glow-sticks.[24]

The immediate outcome of a chemiluminescent process is an excited electronic state. This state subsequently decays to an electronic ground state, emitting light through either an allowed transition (similar to fluorescence) or a prohibited transition (similar to phosphorescence), depending on the spin state of the produced electronic excited state. Chemiluminescence is distinct from fluorescence and phosphorescence except that the electronically excited state is produced by a chemical process instead of by photon absorption. It is the polar opposite of a photochemical reaction, which uses light to catalyze an endothermic chemical process. Here, light is created as a result of an exothermic chemical process. Chemiluminescence may also be induced electrochemically; this is referred to as electrochemiluminescence. [25]

The first chemiluminescent chemical was 2,4,5-triphenylimidazole (lophine), which emitted light when combined with potassium hydroxide in ethanol solvent in the presence of air in 1877[26]. The luminol test is a well-known example of chemiluminescence in a laboratory setting [27].

Whenever chemiluminescence occurs in living creatures, it is referred to as bioluminescence. As mentioned before, a clear example of chemiluminescence is the process through which a light stick emits light, and it is described in figure 11. [28]



Figure 11. Example of chemiluminescence. A glowing stick. Taken from reference [28]

2.1.1.8 Triboluminescence

When a force is applied to a solid substance, this type of luminescence arises. The name triboluminescence derives from the Greek word "tribe in," which implies rub. Triboluminescence (TL) may be achieved in various methods, including by shredding crystals or by moving a liquid over the surface of a solid material[29].

First, what is triboluminescence? It is a tribology process that results in the creation of light when materials come into contact with one another. The origin of the triboluminescence is derived from a mixture of the Greek word for rub "tribein " and the Latin word for light, "Lumin". Frictional mobility is the action of rubbing, scraping, crushing, or shredding a substance; this action results in electrostatic force by splitting and rejoining the electrical currents. However, this optical phenomenon has been extensively studied, and there is still much more to learn about it. Therefore, the term triboluminescence was created in 1888 by Wiedemann and Schmidt to refer to an emission of light that is not caused by an increase in heat that happens when such compounds are crushed. [29]

Francis Bacon (1620) is credited with being the first witness of the triboluminescence phenomenon, claiming that sugar crystals sparkle when shattered. After that event, Robert Boyle, in 1663, established the veracity of Bacon's research on triboluminescence and the sparkling effect caused by rubbing or scratching.[30]

A technique for seeing triboluminescence is by using a well-known triboluminescence example, such as the Wint-o-green. When Lifesavers (Lifesaver is a registered brand of Lifesaver, Inc.) are cracked open in the air, powerful triboluminescence may be seen. Triboluminescence occurs when asymmetrical materials are shattered. Electrical charges are separated by the crack and rejoin to ionize the air. The ionization of nitrogen in the air generates invisible UV light[31]. Triboluminescence is only observable when a substance catches the ultraviolet light and releases it in the visual spectrum (fluorescence [32]. Numerous additional substances display triboluminescence—sugar squares in their natural state, as well as any sweet produced with sucrose. When most sticky tapes, which include duct tape, are ripped, they produce light. Calcite, feldspar, fluorite, and quartz, among others, show triboluminescence when mechanically strained. [33].

There seem to be numerous applications to this subject, hence why the concept of triboluminescence has indeed been extensively studied by scientists in different areas such as biology, physics, electronics, and its applications in the aforementioned domains. The housing industry is one of the diverse applications, with the majority of research on tangible goods focusing on a variety of factors to better understand their use and advantages. Utilizing image processing and machine learning algorithms, triboluminescent materials are frequently employed in the construction sector for fracture identification and final inspection. This fracture detection appears critical since it operates as a preventative measure to avert severe harm (Figure 12).[34]. Aich, Appala, and Saleh gathered information in this sector by coating cement mortar cubes with manganese-doped zinc sulfide with the intention to observe and record the luminescence to commence image processing and fracture quantification. The study's findings established a clear correlation between triboluminescent concentration and electrification. [35]

The triboluminescence phenomenon may be employed to create intelligent structure sensors generally. These sensors may be used to detect and monitor damage to civil, aerospace, and military facilities, as well as spacecraft and airplanes. [36]. Triboluminescent sensor systems offer the potential for wireless, and dispersed sensing, enabling continuous monitoring in real-time and making them desirable for a range of manufacturing applications. Additionally, they may be employed as strain, fracture, and degradation detectors. [8]



Figure 12. Triboluminescence application illustration. Taken from reference [34]

2.1.1.9 Sonoluminescence

Sonoluminescence is a physical phenomenon that happens when related ultrasound is in an aqueous environment. The mechanism that occurs is that the ultrasound provokes some bubbles to come up that also collide with each other, then at the time of the collision, it creates heat. Therefore by these circumstances, the electron detaches from the nuclei of the atoms, so the plasma is generated to produce visible light [37].

Ultrasonic irradiation of liquids may indeed create illumination, labeled "sonoluminescence," as Frenzel and Schultes demonstrated in 1934 using water. Sonoluminescence is a phenomenon caused by sonic cavitation. Multiple-bubble sonoluminescence (MBSL) and single-bubble sonoluminescence (SBSL) are two types of sonoluminescence [38]. Because cavitation is a nucleated phenomenon and liquids typically include a significant number of nuclei, the "cavitation zone" formed by spreading or stationary sound waves involves the combination of a vast number of interacting bubbles scattered across a vast area of the fluid. may powerful Cavitation be enough to generate multiple-bubble sonoluminescence. For somewhat technical but readily attainable circumstances, it is now demonstrated that a single stable gas bubble may be driven into giant magnitude pulses that emit sonoluminescence on each acoustic period. [39].

In certain circumstances, the acoustic force acting on a bubble may be utilized to counterbalance its float, therefore stabilizing the bubble in the fluid through acoustic floating. It enables a detailed analysis of the dynamic properties of a single cavitating bubble (Figure 13), either theoretically or experimentally.[40]



Figure 13. SEM picture of sonochemically produced hemoglobin protein microspheres. Taken from reference [39]

3 Review of luminescent polymers

3.1 Luminescence in conjugated polymers

3.1.1 Conjugated polymers

Firstly, it is needed to be mentioned about conjugated polymers. Therefore, they are substances that a backbone of altering single and multiple bonds yields into π -conjugation by an overlap of the π -orbitals in the atoms, forming the band structure, which is a continuity of energy states. Conjugated polymers are interesting for different functions because of their characteristics.

One of their most unique characteristics is that their molecular arrangement can be modified; therefore, this results in a suitable material for an enormous number of exceptional uses. Conjugated polymers possess the capability to reach similar electrical properties compared to some inorganic semiconductors. Nonetheless, their chemical arrangement is way more complicated, and they are considered similar to biomacromolecule's structure. [41]

3.1.2 Conjugated luminescent polymers

Previously to review the luminescent conjugated polymers especially, it is convenient to recapitulate about two kinds of luminescence mentioned before: fluorescence and phosphorescence. Thus, the difference between these two kinds of luminescence is that fluorescence is a radioactive decay mechanism of a molecule from its singlet excited state to the singlet ground state. On the other hand, phosphorescence is a radioactive decay mechanism that starts in a triplet excited state to the singlet ground state. [42] Having these concepts, one of the very first studies about conjugated luminescent polymers was analyzed by Holdcroft et al. [43]. The investigation was performed over the conjugated polymer poly(3-hexylthiophene), see figure 14, (P3HT) that presented luminescence in the form of phosphorescence. In that report, some other examples presented luminescence in the form of phosphorescence, such as α -terthiophene, which is correlative as polythiophene, which shows an exact spectrum to the α -terthiophene. Later different investigations about the phosphorescence of conjugated polymers are presented, for instance: methyl-substituted lad-der-type poly(para-phenylene) (MeLPPP), also it is exhibiting the dialkoxy-substituted poly(para-phenylene) (dC80PPP), and finally it can be seen in the following figure, poly(9,9-di-n-octylfluorene) (PFO), and poly(3,6-carbazole) by-products (PCBP).[42], [43]



Figure 14. Examples of polymers and oligomers presented in the first studies of luminescence of polymers. Taken from reference [42]

Due to the high level of interest in these types of luminous polymers, both academic and industrial, significant work has been spent on the design and synthesis of diverse conjugated polymers.[44] Considerably amount of studies have been conducted to generate high efficiency of light-emitting polymers that emit at adjustable frequencies, with extended lifespan, and color pure. [45] Conjugated polymers are being employed in a variety of optoelectronic devices, including light-emitting diodes(LEDs), and field-effect transistors among others. [46]

Numerous polymeric substances have been widely researched as light-emitting compounds, some examples including poly(p-phenylenevinylene) (PPV), polythiophene (PT), poly(p-phenylene) (PPP), poly(phenyleneethynylene) (PPE), and polyfluorene (PF). [47]

3.1.3 Examples of luminescent conjugated polymers

In the following examples of chemical structures (Figures 15 to 19), there are going to be explained about de characteristics of some luminescent polymers.

3.1.3.1 Boron and Aluminum Quinolates

Organoboron quinolates are emerging as promising materials for luminous systems due to their potential use as electrical conductors and emissive elements in organic light-emitting diodes (OLEDs) [48][49].

Organoboron quinolates are a significant family of chemicals that have shown broad use in chiral boron catalyst identification, trace metal measurement by fluorescence reaction, insecticides, bactericides, and antibiotics.[50] It is their luminescence that has received much attention lately. In 1987, Tang and VanSlyke discovered the electroluminescent characteristics of aluminum quinolates (AlQ3) and similar derivatives, and they are now extensively employed as components for emitting and electron-conducting structures in organic light-emitting systems (OLEDs) [51]. Boron and aluminum quinolates are presently used in vacuum deposition processes for device manufacture. On the other side, aqueous processing techniques, such as ink-jet print, are gaining increasing interest as a possible low-cost option. As a result, incorporation of the inorganic component within polymer structures has opened up novel avenues [52][50][47].



boron quinolate

Figure 15. Boron quinolate chemical structure. Taken from reference[50],[47]



Figure 16. Aluminum quinolate chemical structure. Taken from reference[50]

3.1.3.2 Boron diketonate



Figure 17. Boron diketonate chemical structure. Taken from reference[53],[47]

Organoboron diketonate is indeed a boron light-emitting compound with high molar absorption coefficients and quantum yields. [54]. It could present luminescence with low emission and a high phosphorescence [55].

3.1.3.3 Boron dipyrromethene



Figure 18. Boron dipyrromethene chemical structure. Taken from reference[47]

Boron dipyrromethenes and their derivative products are a category of strongly luminescent materials that have been discovered. Fluorophores are widely used for biochemical classifying, photonic molecular devices, beam dyes, organogelators, and light-emitting equipment. Due to its high quantum efficiency, reduced interference crossing percentages, big mole ratio absorptivity, and outstanding photostability[56].

The inclusion of boron dipyrromethenes as luminescent chromophores into polymeric side chains and silica matrix is advantageous for optoelectronic devices such as dye lasers[47],[57].

3.1.3.4 Pyrazabole



pyrazabole

Figure 19. Pyrazabole chemical structure. Taken from reference[47]

Pyrazabole is a very robust boron heterocycle that easily accepts a wide variety of compounds. Numerous uses of pyrazaboles have been described, such as their broad applications either building blocks for liquid crystals or as excellent connectors for ansa-ferrocenes in the formation of active container structures for supramolecular uses.[47][58]

3.2 Luminescence in non-conjugated polymers

3.2.1 Non-conjugated luminescent polymers

Luminescence contributes significantly to the advancement of several research frontiers in computing and imaging[59]. Polymeric luminogens are a luminous substance that has generated considerable scientific attention, partly due to their structural diversity and ease of functionalization[60]. Non-conjugated luminescent polymers are a family of polymers that exhibit light emitting features in the absence of conjugated systems, as do traditional polymeric luminogens.

Highlight the benefits of non-conjugated luminescent polymers over conventional polymeric luminogens, such as their high emission brightness. Also, after preparation into aggregated or solid form, it is estimated that the photophysics and chemistry of non-conjugated luminescent polymers become more sophisticated than conjugated luminescent polymers. Not only will our comprehension of optical processes be unaffected by aggregation-caused quenching (ACQ) improve, but the mechanism [61]. Non-conjugated luminescent polymers (NLPs) have a wide variety of applications, ranging from OLEDs to chemo-sensing and, as previously indicated, luminous drug carriers[62].

3.2.2 Examples of non-conjugated luminescent polymers

3.2.2.1 Non-conjugated luminescent polymers as drug carriers

Whereas the photo-physics of non-conjugated luminescent polymers (NLPs) has been intensively investigated until lately, their luminescence has been widely embraced in the literature for several years. Another example comes from a lysine-based cationic dendrimer that lacks a fluorophore. The dendrimer was synthesized as a cell transport nanoprobe[63]. Another example comes from chitosan, a kind of natural polymer formed when chitin is partially deacetylated. Chitosan's inherent luminescence has helped in characterizing the degradability and cell attachment capabilities of chitosan fiber-mesh scaffolding (Fig. 20) [64]. Furthermore, the pores of a chitosan-gelatin layer on the surface of a titanium implant were effectively used as a fluorescent microscope by using chitosan's emissive ability. This technique enables the coated implant's microstructural and physicochemical characteristics for osteogenesis [65]. Besides imaging applications, chitosan is positively charged due to the presence of amine groups. Nanoparticles for plasmid transfection and RNA interference have been created using ionic crosslinking with tripolyphosphate (TPP) [66], with no visible cellular injury or symptoms of irritation after intramuscular injection of such nanoparticles into mice.[61]



Figure 20. Image of chitosan fiber mesh. Taken from reference [61]

3.2.2.2 Comparative table of different non-conjugated luminescent polymers

Polymer	Origin	Optical Features	Application as drug carriers
Cellulose	Natural	Blue luminescence was reported from the cellulose matrix in filter paper when excited at 325-375 nm.	Hybrid gels derived from high-amylose starch and microcrystalline cellulose have been shown to float in the stomach and provide sustained drug release for oral medication administration. The freeze-drying technology was used to create cellulose nanofiber aerogels. Aerogels with strong floatability and mucoadhesive characteristics have been developed for oral medication administration.
Chitosan	Natural	When chitosan fibers were excited at 488 nm, green fluorescence was seen.	Minocycline was put into an ionically crosslinked chitosan-based hydrogel, which effectively improved wound closure in a full- thickness excisional wound model. A copolymer composed of chitosan and PEI was discovered to be excellent in delivering plasmids to cancer cells.
Poly (aminodo amine) "PAMAM"	Synthetic	On excitation at 390 nm, blue luminescence was seen from an aqueous solution of a G4 NH2-terminated <i>PAMAM</i> dendrimer.	A copolymer composed of chitosan and hypromellose has been used to deliver medications over an extended period of time. A carboxyl-terminated <i>PAMAM</i> dendrimer was grafted with PEG methyl ether (mPEG) and shown to be highly biocompatible for the delivery of carboplatin (CPT).
PEG	Synthetic	On excitation at 450 nm, green fluorescence was seen from PEG in the drug-loaded matrix.	PEG-conjugated pyrrole-based polymers demonstrated to self- assemble into soft nanoparticles capable of delivering drugs and releasing them continuously.
Sodium Alginate	Natural	When sodium alginate solid particles were excited at 312 nm, blue fluorescence was seen.	Multiple medicine co-delivery has been shown using multicompartment microgels made from sodium alginate through a microfluidic electrospray method. The sodium alginate core-shell hydrogel beads have been developed for sustained medication release.
Starch	Natural	When starch solid granules were excited at 365 nm, blue fluorescence was seen.	Composites were synthesized from a starch derivative utilizing an emulsion-template approach for the simultaneous delivery of hydrophilic and hydrophobic medicines.

Table 1. Comparative table of examples of non-conjugated luminescent polymers. Taken from reference [61]

3.3 Luminescence in polymers with hydrogen bonding

3.3.1 Hydrogen bonding in polymers

Typically, a hydrogen bond or hydrogen bridge is an intermolecular force, although it may also occur when separate sections of a molecule become intramolecular. This bond is formed via dipole-dipole interactions and is usually seen in combination with a negatively charged oxygen, fluorine, or nitrogen atom. This results in the electronegativity difference between the two polar molecules.[67]

In general, a hydrogen bond is defined as a set in which a hydrogen atom is sandwiched between two atoms X and Y — ideally in the linear configuration X– $H \cdots Y$ — with the distance between their nuclei considerably smaller than the sum of their van der Waals radii and proton diameter, the creation of a hydrogen bond causes the X– $H \cdots Y$ structure to contract (Fig21).[68] Hydrogen bonding is a substantial non-covalent force that is commonly involved in the solid-state formation of supramolecular complexes. It has long been recognized in the area of photo-physics that the formation of hydrogen bonds between luminogens may stabilize their molecular structures. [69] In comparison to covalent bonds (155 kJ/mol), hydrogen bonds have a weaker attractive force (5 to 30 kJ/mol). Hydrogen bonding is a substantial non-covalent force that is commonly involved in the solid-state formation of supramolecular complexes. It has long been recognized in the area of photo-physics that the formation of hydrogen bonds between luminogens may stabilize their molecular structures. [69] In comparison to covalent bonds (155 kJ/mol), hydrogen bonds have a weaker attractive force (5 to 30 kJ/mol). Hydrogen bonding is a substantial non-covalent force that is commonly involved in the solid-state formation of supramolecular complexes. It has long been recognized in the area of photophysics that the formation of hydrogen bonds between luminogens may stabilize their molecular structures. [69]



Figure 21. Hydrogen bonding representation of phenol multimer. Taken from reference[68]

3.3.2 Examples of luminescence in hydrogen bonding

While conventional luminogens exhibit strong π - π interactions, this technique has the drawback of decreasing the emission, limiting its use. It was discovered that some non-coplanar luminogens are not luminous in solution but are extremely emissive an aggregate state. This type of emission as a result of aggregation correlates with the effective limit of intramolecular rotations and vibrations (RIR and RIV). The primary explanation for the absence of emission in the diluted solution state is given by rotation- and vibration-coupled molecular interactions between the luminogen and the solvent molecules that are abundant in the diluted solution state, resulting in non-radiative decay of the excited species.[70] Hydrogen bonding may be employed to aid in the self-assembly of structures. Hydrogen bonds are orientated in accordance with the direction of the paired contact, and molecules physically joined by hydrogen bonds may be considered a structural assembly capable of effectively locking the rotation. The salicylideneazine derivative of 2 is employed in this investigation (CN₄OH). It is composed of two six-membered enolimine rings that are linked together by intramolecular hydrogen bonds(Figure 22). [70]



Figure 22. Example of hydrogen bonding. Taken from reference [70]

3.4 Composite and hybrid luminescent polymers

It is essential to be clear about the concept of what a composite material means, therefore a composite material or, in this topic, a composite polymer is the one that is formed from two or more components. These different components possess noticeably different physical or chemical compositions and characteristics. Then they are blended to create a material with features dissimilar to the original single elements. The single components of the final composite material or polymer can be easily distinguished and continue detached. [71] This concept is also applied to luminescent polymers; they can be attached with different kinds of materials, for instance, nanoparticles.

3.4.1 Luminescent Polymers with nanoparticles (composites)

3.4.1.1 Polymer dots

Semiconducting polymer nanoparticles have garnered substantial importance lately due to their exceptional properties as fluorescence sensors. These are nanoparticles primarily composed of π -conjugated polymers and are referred as polymer dots due to their tiny size and intense luminosity. They are helpful in various applications, including fluorescence imaging and biosensing[72]. Polymer dots are polymers that have been aggregated or cross-linked from linear polymers or monomers [73]. Polymer dots exhibit extraordinary photophysical features, high extinction coefficients, high single-particle brilliance, and photostability. Additionally, polymer dots have excellent remarkable biocompatibility, adjustable optical and surface characteristics, and colloid proportions. Numerous research and viewpoints imply that polymer dots are a subgroup of conjugated polymer nanoparticles. As previously said, polymer dots denote both tiny particle size and a high degree of brilliance. Polymer dots might thus be regarded as a branch of conjugated polymer nanoparticles. 11 To be congruent with the concept of a tiny "dot," polymer dots should have a width of less than 20-30 nm, ideally in the range of 5-20 nm [74].

3.4.1.1.1 Luminescence in conjugated polymer dots

Conjugated polymer dots, also known as polymer nanoparticles, are unique, organic nanomaterials with sizes of 1–100 nm. They are composed of π -conjugated organic polymers. Compared to conventional organic small molecules, semiconductor quantum dots, and inorganic nanomaterials, polymer dots have many applications in bioimaging, detection and identification, and drug delivery. They are owing to their unique optical properties, diversified structure, ease of surface functionalization, and excellent biocompatibility. [75]

3.4.1.1.2 Luminescence in non- Conjugated polymer dots

Non-conjugated polymer dots, a subclass of Carbon dots, have attracted growing interest in recent years[76]. They feature aggregated polymer structures. These are distinct from conjugated polymer dots, which are formed by the assembling of fluorescent-conjugated polymers. This non-conjugated polymer may be synthesized by dehydration, condensation, carbonization, or assembly.

The photoluminescent centers in these preparations are assigned to the generated carbon cores or fluorophores. Polymer dots are very promising as innovative luminous materials due to their ease of surface functionalization. [73]

3.4.2 Hybrid luminescent polymers

Initially, luminous materials were mostly inorganic and consisted of transition metals or rare-earth metals. Following excitation, these materials display wide emission bands due to parity-allowed electron transitions. The host lattice has a significant effect on the emission wavelengths, which are primarily determined by the coordination number of the cations, the anionic rare-earth metal bond lengths, and symmetry[77]. Over the years, various synthesis procedures have been developed with the goal of improving these materials' excitation durations, photo/thermal stability, quantum efficiency, and cost. As a result, hybrid luminescent materials seem to be a viable option. Due to its potential uses in optical displays, biological imaging, chemical sensing, and security systems, hybrid luminescent materials have garnered recent interest. These materials benefit from simple structural adjustment and processing, which enables the production of soft and flexible optical devices.[78] After reviewing the most recent breakthroughs in the design principles of hybrid luminous materials and their prospective applications, there are three major building obstacles. The first is time-related, with the goal of increasing durability, photothermal stability, and luminescence lifespan. The third issue is space, or more precisely, the hybrids' spatial organization, orientation, state of aggregation, and chirality. Finally, but certainly not least, energy is defined in terms of quantum efficiency, luminescence color, wavelength, and energy transfer. These three characteristics expand the scope of future study in this field. The next section will describe some instances.[79], [80]

3.4.2.1 Examples of Hybrid luminescent polymers

This section discusses inorganic–organic and polymeric–organic hybrid luminous polymers. The first, owing to their applications in drug delivery, catalysis, energy conversion, and storage, coupled inorganic nodes and organic connecting groups are highly valued in the industry. About inorganic-organic molecular hybrid materials, an appropriate example is that metal-organic frameworks (MOFs) are a subset of coordination polymers (CPs), consisting of networks of metal clusters or metal ions connected by organic ligands. MOFs with luminescent properties are composed of noble metals and rare earth elements (Au, Pt, Ru, Ir, Tb, and Eu). For the second, covalently attaching phosphors to polymer matrices, via intermolecular interaction, is a recently developed technique for implanting phosphors into a rigid matrix and generating persistent luminescence reactions such as free radical copolymerization, covalent cross-linking, and ring-opening polymerization. All of these are facile ways for producing polymers. [81]–[83]

3.5 Conventional luminescent polymers

Conventional luminescent polymers are those that have large π -aromatic building components. Prior to discussing conventional luminescent polymers, it is necessary to understand conjugated polymers. These conjugated polymers are macromolecules distinguished by an alternating backbone chain composed of double and single bonds. Numerous optical and valuable properties may be seen as a result of the overlapping p-orbitals that form a configuration of delocalized π -electrons. The backbone chain of a polymer, as previously stated, is the most extended sequence of covalently bound atoms that collectively form the molecule's continuous chain.[3]

Furthermore, the second concept, delocalized π electrons, refers to electrons that span many atoms. Typically, electrons are bonded to a single atom in materials, and atoms are kept together by the interplay of their charges. For those π -electrons with a neighboring sigma bond, delocalization occurs. Due to their high emission characteristics, these compounds have attracted significant interest in a range of applications, including organic light-emitting diodes (OLEDs), photovoltaic panels, and biomedical imaging. Despite their widespread usage, the difficult synthesis and toxicity of large conjugated systems, their poor water miscibility, and limited resistance to photobleaching limit their future development and utilization. Additionally, they are very luminous in aqueous systems but emit weakly or not at all when concentrated or aggregated, owing to the aggregation-caused quenching (ACQ) phenomenon. [3]

3.6 Non-conventional luminescent polymers

This is a novel class of photoluminescent materials that lack large π - π conjugated configurations and exhibit specific properties in their emission phenomena, including the absence of delocalized electron excitation and the ability to behave as a group rather than as separate units. Additionally, the advantages of these types of polymers over the typical ones stated before include a more accessible method of manufacture, a cheaper cost, and less environmental impact. These items may be used for the appropriate and precise purpose.[84], [85].

Due to the difficulties associated with conventional luminescent polymers, researchers have discovered a novel category of photoluminescent compounds free of large π - π conjugated groups, dubbed non-conventional luminescent polymers. [84] This novel class of luminous structures often contains a solitary ring structures or contains other subcategories such as (CN, C=C, -OH, and -NH2), as well as substances such as sulfur, phosphorus, oxygen, and nitrogen. Compared with normal luminogens, the emission properties of nonconventional luminescent polymers are pretty distinct. To begin with, they do not need the stimulation of delocalized electrons. On the other side, they behave as a group of molecules instead of as a solitary or autonomous unit, resulting in significant emissions in the concentrated/aggregated form. [86] Additionally, these kinds of luminescent polymers have several advantages over conventional polymers, including ease of production, relatively inexpensive, environmentally friendly nature, biocompatible, and low or non-toxicity, which enables them to be shaped into potential materials for achieving competitive advantages. [87]

Poly(amido-amine) polymers are a kind of dendrimer composed of repeatedly branching amide plus amine functional group subunits. [88] Poly(amido-amine) (PAMAM) is a good model of a synthetic polymer that exhibits non-conventional luminescence. [89] Since Tomalia et al. initially synthesized PAMAM dendrimer in 1985, the polymer's weak emission has been increased several times. [88] Following that, Tucker et al. hypothesized in 2000 that the faint although noticeable fluorescence of PAMAM was due to intrinsic emission from the n- π^* transition corresponding to the amide groups.[90] This first study of Poly(amido-amine) dendrimer marked the start of a systematic investigation into non-conventional luminescence. Afterward, several kinds of nonaromatic luminous polymers were developed for foundational research and performance optimization. [6]

3.7 Mechanisms

3.7.1 Mechanisms of luminescence in polymers

The luminous procedure involves an electron being excited towards the metastable state, being activated to the emitting level, and a prohibited shift between the emitting and ground levels. The metastable condition is skipped when the activation energy is greater. Under elevated temperatures, the metastable electron overcomes a greater potential threshold, resulting in less radiation interaction with the activating element.

Since excitation of an electron in this condition is required prior to emissions may happen, the metastable phase frequently alludes to an electrons trap. The change in fluorescence intensity with heating rate during ongoing stimulation indicates luminous efficacy and gives insight into how the luminescent mechanism works.[91]

3.7.1.1 Aggregation-caused quenching effect

When traditional fluorophores are gathered or aggregated, their light emission is often reduced. Due to this action, luminescence is often attenuated or quenched at high congregations of fluorophores; this process is referred to as concentration quenching.[92] A potential cause of the quenching process is related to the development of conglomerates, or in this scenario, called aggregates, which is why the concentration quenching effect is commonly known as aggregation-caused quenching. [93] The quenching effect associated with aggregation has also been reported in inorganic luminescent substances, for instance, quantum dots. [94]

A more effective method to comprehend the aggregation-caused quenching effect is to illustrate it using an example, as shown in figure 23. The image represents a mixture of N,N-dicyclohexyl-1,7-dibromo-3,4,9,10-perylenetetracarboxylic diimide (DDPD), dissolved in Tetrahydrofuran (THF), which is an organic solvent that has a low boiling point, low viscosity, and high solubility.[95] The combination of DDPD and THF is very luminous. When water is mixed with THF, the luminescence associated with the union of the two substances is diminished. As the insolubility of DDPD with water rises, the luminophore concentration of DDPD particles tends to agglomerate. This occurs because as the water concentration is augmenting, the THF and water mixture's dissolution ability decreases to the point where the majority of the DDPD molecules agglomerate. At the end of that process, it is shown that DDPD's luminescence is entirely quenched as a consequence of aggregate development. [93]



Figure 23. ACQ effect in a solution/suspension of DDPD. Taken from reference[93]

DDPD particles feature a perylene center body in the shape of a disc. When DDPD particles experience a conglomeration, the perylene rings could encounter intense π - π layering interplay because single-layer luminescent particles or molecules, as in this scenario perylene, tend to aggregate as discs accumulate on top of each other, and this frequently results in the inhibition of luminescence. The accumulation of the discs results in the generation of non-favorable molecules as excimers (excited dimers formed by the association of excited and unexcited molecules). As a result, the aggregation-caused quenching effect is noticed.[96] This effect is very frequently seen in most aromatic compounds [97] A fundamental cause for the appearance of aggregation-caused quenching effect is that traditional or conventional luminescent molecules are usually composed of planar aromatic hydrocarbon chains, such as mentioned before, perylene, which is a polycyclic aromatic molecule that exhibits a kind of blue fluorescence. [98]



Figure 24. representation of ACQ effect. Taken from reference. [99]Emission takes place when fluorophores are in solution, and it is non-emissive when they are aggregated.

Since luminescent properties of a compound are primarily determined by electronic conjugation, a method consists of augmenting the breadth of π - π conjugation by linking several aromatic rings. In this way, with larger chains of aromatic rings with better luminescent properties in solutions, the aggregation-caused quenching effects may increase as the probability of larger luminescent molecules forming excimers increases.[96]

The quenching effect generated by aggregation is often regarded as harmful in practical or industrial uses. For instance, luminescent substances have been employed as sensors to determine the concentrations of ionic groups in water samples.[100]

Aggregation-caused quenching effect is also a key barrier in manufacturing organic light-emitting diodes, in which luminescent compounds or luminophores are employed as slim solid films. Due to the lack of solvent in the solid state, the luminophore density increases to the limit, and the aggregation-caused quenching effect results in more intense. [51] Due to the fact that the aggregation-caused quenching effect is detrimental to diverse uses, various researchers have devised multiple attempts to address the issue. Physical procedures or different chemical reactions are often used to prevent the production of luminophore aggregates. [101]

3.7.1.2 Aggregation-induced emission effect

The aggregation-induced emission effect is the contrary to the well-known aggregation-induced quenching phenomenon. Aggregation-induced emission effect is helpful to purposefully using the spontaneous aggregation process of luminescent molecules, rather than battling against it.[93] Luminescent molecules have an inherent proclivity for aggregation formation in concentrated liquids and the solid phase. Tang et al. (2001) developed an unusual luminogens structure wherein aggregates of luminophores behaved in a manner that luminescence could happen instead of diminishing the luminescence as it does in standard luminogens systems. [102] The research discovered that although a series of silole derivatives did not display luminescence in diluted mixtures, they were intensely luminous when aggregated in concentrated mixtures or a solid-state. [103][104]

Aggregation-induced emission occurs in a wide variety of molecular systems and gives novel concepts for creating luminescent substances that are structurally distinct from the previously stated aggregation-induced quenching systems. [105] Aggregation-induced emission mechanism provides a convenient alternative to the quenching effect generated by the aggregation of luminescent molecules.[94] Aggregation-induced emission is a luminous phenomenon in which a substance shows improved luminescent characteristics when it is aggregated due to the limitation of intramolecular movements, vibrations, or rotations. [94]

Hexaphenylsilole (HPS) is a recognized exemplar of an aggregation-induced emission luminogen; it does not present luminescence when is diluted in a mixture, by using a great solvent such as it is tetrahydrofuran (THF), but its luminous emission is strong when its molecules aggregate in a lowquality solvent, such as THF mixed with a large excess of water, as shown in the following figure. In contrast to the aggregation-caused quenching luminophore, HPS has a helical turbine structure, as seen in the picture, which inhibits the $\pi - \pi$ stacking contact between the aggregation-induced emission luminogens units. [99]



Figure 25. Representation of AI effect. Taken from reference. [99]. Emission takes place when fluorophores are aggregated, and it is non-emissive when they are in solution.

The reason that conglomeration brightens the emission of aggregation-induced emission luminogens is because basic physics tells that any particle motion, whether rotation, vibration, or whatever else that produces work, spends energy. In HPS, the six-phenyl outer molecules may spin continuously around the silole nucleus. Intramolecular spinning is operative in the liquid diluted mixture, using excited-state energy through a non-radiative relaxation route. As a consequence, HPS's fluorescence is diminished. Although, in the aggregate state, such spinning or twisting is controlled by physical restrictions, which prevent excitons from decaying non-radiatively. [99] [106]–[108]

The aggregation-induced emission luminogens are promising materials for practical uses because to their luminescence 'switch-on' property in the aggregate state.[93] The aggregation-induced emission effect is often caused by a restriction of intramolecular motion (RIM), which comprises restriction of intramolecular rotation (RIR) and restriction of the intramolecular vibration (RIV). In simplest terms, the restriction of intramolecular motion (RIM) process results in structure rigidification of the different luminous substances [99]



Figure 26. Aggregation's effect on the luminescence behavior of a polymer. Taken from reference.[93]

3.7.1.3 Crosslink-enhanced emission effect

The crosslink-enhanced emission (C-EE) effect was first initially shown in 2014 and was formally presented in 2015 as a unique luminescence mechanism for non-conjugated polymeric dots. [109][87] Non-conjugated polymer dots are a new family of nanoparticles with aggregated or crosslinked polymeric arrangements. Initially, crosslink-enhanced emission was interpreted as an immobilizing mechanism that was primarily relevant to non-conjugated polymer dots independently, with the enhancement attributed to limited vibration and rotation (similar to the past mechanism of aggregation-induced emission luminescence). Remarkably, crosslinking is a characteristic of a large number of polymer structures. Crosslink-enhanced emission may account for some unusual luminescence properties seen in other polymeric systems, including increased quantum yield (QY), wavelength shifts, and also radiative procedure transformation from fluorescence to phosphorescence. [110]

C-EE is a crosslinking-induced enhanced effect on luminescence. Crosslinking may be classified broadly as chemical or physical, and the related interactions as covalent or noncovalent bonding, which encompasses numerous types of chemical bonds as well as extended spatial interactions.[87] The first kind of chemical bonding is the covalent bond, which offers a persistent and firm bonding connection in crosslink-enhanced emission. It often manifests itself in the production of more rigid structural components, reducing non-radiative transitions and sometimes developing novel luminous aggregations. Polyethyleneimine (PEI) is a polymeric structure that exemplifies the C-EE covalent bond.[87], [109]

The following kind of chemical bond in crosslink-enhanced emission is the noncovalent bond, which is a more general kind of interaction that is not limited by the restrictions of covalent bond formation.

Each kind of noncovalent-bond interaction contributes equally to luminescence amplification. Supramolecular interaction C-EE, ionic bonding C-EE, and confined-domain C-EE are the three non-covalent bond interactions used in crosslink-enhanced emission.[6]

3.7.1.3.1 Supramolecular-interaction C-EE

Supramolecular interactions are the most prevalent form of noncovalent bond interaction. They include hydrogen and halogen bonds, the van der Waals force, π - π stacking, host guest interactions, and coordination. Due to the variety and dynamic properties of these interactions, it is possible to produce reactive photoluminescence characteristics through supramolecular interaction C-EE.[111]

3.7.1.3.2 Ionic-bonding C-EE

Ionic bonds constitute noncovalent chemical bond interactions that are quite strong. Ionic bonds are fundamentally a result of electrostatic interactions, which comprises both electrostatic attraction and repulsion. Ionic connections are generated when the forces of attraction and repulsion establish an equilibrium.[6]

3.7.1.3.3 Confined-domain C-EE

As an essential complement to noncovalent-bond C-EE, confined-domain C-EE provides a through-space interaction. Crosslinking and entanglement, limit the luminophores inside a constrained region, causing electron clouds to approximate or also overlap. Localized orbitals or clusters of orbitals interact directly or indirectly via other chemical connections. This last interaction is capable of operating across an astonishingly long radius. If indeed the preceding crosslinking is taken as the result of bonding, the confined-domain C-EE might be understood as a more profound orbital interaction.[6]

3.8 Applications of luminescent polymers

3.8.1 Organic light-emitting diodes (OLEDs)

Organic semiconductive thin films over the last decades received significant attention from many researchers all over the world due to the adaptability and ease of preparation of these kinds of films, resulting in a wide range of actualworld purposes in electronic and electrical materials. For instance. photodetectors, transistors, and also light-emitting (LEDs).[112] diodes Therefore, in this regard, the investigation of organic semiconductors in LEDs has advanced rapidly as a result of their usage of them in flat displays, and the effectiveness of the experimental materials has achieved a suitable level for real world applications, which could result in massive commercial production in the coming years. Electroluminescence is a phenomenon characterized bv electrically induced radiative emission, occurring in a wide variety of standard semiconductors, and organic electroluminescence were initially observed and widely explored in the 1960s. [113] Within those initial researches, it was discovered that the combination of electrons injected from one electrode and holes injected from the other electrode played a critical part in the light emission mechanism. In 1987, researchers developed devices with sufficient low operating voltage levels and appealing electroluminescence efficiencies using two-layer organic light-emitting diodes (OLEDs) using convenient smallmolecule components and architectures.[114], [115]

In general, an OLED (optical modeling and optimization of organic light-emitting diodes) was first introduced by Eastman Kodak in 1987 [116]. Since then, OLEDs have been assigned as promising technologies to contribute to future displays [117]. Nowadays, OLEDs are valued in some industries whose interests are displays and lighting. Besides, it is now seen as a field of investigation that inspires and boosts the development of OLED technology devices[118].

OLED devices have been introduced based on three generations of emitter materials built on fluorescence which is the first generation, phosphorescence, which represents the second generation, and finally, the third generation, which is the thermally activated delayed fluorescence. However, it is said by the academy's investigation that fourth-generation OLEDs are being developed[119].

The use of OLEDs in displays may have the following features: super-light, paper-thin, flexible enough, and production of a bright and colorful picture. Nevertheless, it is vital to emphasize knowing how a regular light-emitting diode (LED) works and keep in mind clear concepts [120].

Therefore, LED is a junction diode that is an added feature; for example, it makes light produced by electrons that cross the junction [117]. Similarly, OLEDs work like regular LEDs, but instead of using pieces of semiconductor material that are slightly rich in electrons (n-type) and slightly poor in electrons (p-type), they use organic molecules in order to produce their electrons and holes [120]. Therefore, it is crucial to know how an OLED is constructed. It is composed of six different layers where the top (called the seal) and bottom (called the substrate) belong to protective layers, such as glass or plastic.

Consequently, OLED devices are multiple organic layers found between an anode (-) and a cathode (+). Each layer of the OLED performs a vital role. Due to the organic material layers and the recombination of holes, the electrons are excited, and emission is produced. Apart from knowing what an OLED is and how it works, it is also essential to know the types of OLED. First of all, there is the passive-matrix OLED (PMOLED), which is composed of electrically conducting rows and columns, and between these, there are the organic layers [120].



Figure 27. OLED passive matrix representation. Taken from reference.[120]

In the second place, there is the Active-Matrix OLED (Amoled) and unlike the passive matrix, the anode (-) will have a thin film transistor (TFT) the one that has to control over the brightness and pixels that get turned on in order to form an image.



Figure 28. OLED passive matrix representation. Taken from reference.[120]

And finally, there is the third type which is that the white OLED emits a brighter, uniform, and efficient light than fluorescent light. These types of OLEDs have the qualities of incandescent lighting due to the fact that they can be made of large sheets.



Figure 29. White OLEDs. Taken from reference.[120]

OLED displays are better than Liquid Cristal Display (LCD). There are more compact and lightweight, with a greater contrast ratio and a broader viewing angle. It has established itself as a standard in the field of optical displays, particularly smartphones and TVs.[99]



Figure 29. OLED smartphone flexible display. Taken from reference. [99]

3.8.2 Luminescent polymers for bioimage

Cancer has developed into a severe health problem in recent years, posing a danger to people. Even though surgery results in irreparable physical harm, it is a common form of cancer therapy.[121] Fluorescence bioimaging using a tissue-transparent, near-infrared window is a high-resolution diagnostic approach with significant promise for in vivo deep-tissue viewing.[122] Fluorescence bioimaging, compared to other imaging techniques such as ultrasonography, magnetic resonance, and computed tomography, gives more precise spatial features. [104] Additionally, fluorescent bioimaging may be used to see cells and bacteria in live time and determine viability. [123] Various inorganic compounds have been produced and used as fluorescent probes, such as fluorescent dyes, quantum dots, and proteins to accomplish fluorescence bioimaging.[124] Nevertheless, specific properties of the various materials, such as the resulting aqueous solubility, toxicity, and quick photobleaching, therefore these characteristics limit their widespread use in biomedical science.[125]

Due to their extensive uses in cell imaging, cancer detection and treatment, drug administration, and tissue engineering, photoluminescent materials have garnered considerable interest in biomedical and biological domains in recent years. In biomedical applications, conventional fluorescent biomaterials include inorganic quantum dots, rare earth-based nanoparticles, fluorescent dyes, and proteins, all of which have disadvantages.[126] Quantum dots, for instance, posed significant toxicity issues due to the possibility of hazardous ions leakage. Due to the nonbiodegradable nature of rare earth nanoparticles, it is quite simple for them to accumulate in vivo, which may result in long-term toxicity.

Fluorescent dyes are quite widespread in biological research; however, they are often rarely utilized in vivo due to their low photostability and cytotoxicity. Biocompatible fluorescent proteins often suffer from photobleaching, poor quantum yield, and high price. In recent times, fluorescent molecules and nanocrystals encased polymers have been created to address these issues using various fluorescent materials. Consequently, there is an immediate requirement for novel biomaterials that are robust, biodegradable, biocompatible, and photostable. There were fabricated two kinds of biodegradable and biocompatible luminescent polymers poly(silicon-citrates) (PSC) and crosslinked PSC (CPSC) with inherent photoluminescence and improved mechanical qualities. PSC and CPSC have significant potential as nanoparticles for bioimaging and drug delivery, and as tissue regeneration implants for fluorescence tracking.[127]

Coincidentally, self-fluorescent polymers are attractive options for addressing these issues. In contrast to fluorescence polymers, self-fluorescent polymers are formed by covalently attaching fluorescence chromophores or fluorescence dyes to polymer backbones to impart fluorescence features, rather than loading them through non-fluorescent polymer-carriers.[128] Self-fluorescent polymers have gained increased interest in recent years because they more precisely expose the intrinsic fluorescence of polymer backbones. Numerous self-fluorescent polymers have been produced by combining fluorescent molecules with conjugated polymer backbones or heteroatom-containing chromophores.[129]

The first integration technique is a well-established method for producing selffluorescent polymers. Rhodamine, for instance, is a standard fluorescent pigment that may be covalently linked to polymer chains or contained inside polymer structures.[130] Likewise, various innovative and visually appealing fluorescent dyes, including tetraphenylene (TPE) with aggregation-induced emission (AIE) activity, hexaphenylsilole (HPS), distyrylanthracene (DSA), and visible-nearinfrared luminescence, are being produced as fluorescent probes. [131] Selffluorescent polymers may be readily synthesized using these fluorescent dyes by incorporating them into the polymer's main chain, side chain, or star structure. [132]

Due to the synthesis of heteroatom-containing chromophores with distinctive fluorescence emission characteristics, the second integration approach is an innovative way of producing self-fluorescent polymers. On the basis of these factors, numerous poly(amine-esters) containing nitrogen, polysiloxane carrying silicon, and polyester containing oxygen have been produced that generate blue fluorescence for biological imaging.[133] Furthermore, the flexible polymer topology may be used to enhance the design by including novel self-fluorescent polymers that exhibit more diversified fluorescence emission capabilities. Numerous investigations have shown that a hyperbranched poly(amine ester) in solution has a greater fluorescence quantum yield than a linear poly(amine-ester).[134]Due to the enormous potential of self-fluorescent polymers for in vitro and in vivo fluorescence bioimaging, it is critical to developing self-fluorescent polymers that are highly biocompatible and low in cytotoxicity. [129][135]



Figure 30. Representation of fluorescent polymers for bioimaging . Taken from reference.[129]

4 Discussion

The application of diverse luminescent polymers offers considerable improvements in the possibilities that industry and academic investigations for these types of luminescent materials. Luminescence occurs when electrons that are in an excited state, shift to different energy levels, where those transitions can result in either relaxation paths, in radiative decay which present luminescence and also in non-radiative path without the presence of luminescence.[6]

There are different viewpoints about the uses and implementation of luminescent polymers nowadays, in real world applications and theoretical investigations for future development. Ban in 2021,[129] proposed that luminescent polymers containing various fluorescent chromophores (which are the chemical group that gives a molecule its color) have garnered substantial interest in the area of fluorescence bioimaging, due to their customizable topologies and compositions. In this manner, achieving bioimaging is feasible for nowadays applications.

Du and collaborators,[127] in 2016 fabricated two kinds of luminescent-organicinorganic polymers. The first one: poly(silicon-citrates) (PSC) and the second one crosslinked PSC (CPSC). The findings established that not only do PSC and CPSC display intrinsic photoluminescence and good biocompatibility, and they even have the enormous capability for in vivo biological imaging.

Meanwhile in the other hand, Shen in 2011,[125] suggested that polymer coating layers made for quantum dots (QDs), ought to be sufficiently strong to avert harmful metals from being released from QDs during in vivo implantation. Also in studies by Derfus et al., in 2004,[126] and Tan et al., in 2010 [135] is evident the concern of further investigation about the potential cytotoxicity that means to have polymer quantum dots inside a living being, because that cytotoxicity has received little investigation and understanding. At last, even though the polymer layers implemented around QDs enhance the firmness, thus diminishing the harmfulness of them, it is necessary to find a way that polymer-QDs do not remain an extended period of time. A potential concern is how to eliminate polymer quantum dots from a living organism, after having fulfilled their function of bioimaging which complicates substantially the employment of these compounds in further applications.

5 Conclusion

This thesis review covers two main sections. Prior to the theoretical background, a short introduction about polymer concepts, where it is enunciated that they are the conjunction of several units of monomers in one whole integrated chain, that they all bound together to form a polymer.

The first section corresponds to the theoretical background, which details how luminescence occurs, and the classification of the different types of luminescence present in the different materials. The process of luminescence consists in the transition of excited state electrons between different energy levels.

In the sub-classification of luminescence, referring to photoluminescence, there are two main types: fluorescence and phosphorescence. The relationship between these two sub-classifications can be observed in a Jablonski diagram. The diagram representation shows that fluorescence occurs from the emission of the single excited state owing to light absorption. Moreover, on the other hand phosphorescence is the yielding emission from the triplet excited state after an intersystem crossover. Another relation that can be identified between types of luminescence is related to substances that are heated versus substances that are not heated. From that, it is possible to differentiate luminescence from incandescence would be the opposite. It is presumed that the use of luminescent materials is favorable in terms of energy saving. Since, for example, in the case of fluorescent lights consume less energy than incandescent bulbs since they do not have to use heat for their light emission.

Another contrasting distinction that can be discussed in the types of luminescence is the difference that is present between fluorescence and phosphorescence. The main difference that occurs in both this luminescent process is that in fluorescence, the energized electrons produce photons of light instantaneously, and afterward, the electrons restore to their original level. Therefore, this requirement of incoming a source of illumination to produce fluorescence in a material is a limitation for the uses and applications that industry can use in novel materials or products because if no source of light is applied, no more light will be emitted. Thus, there will be no change, or it will be a passive product or material without further potential application in the matter of luminescence. On the other hand, there is phosphorescence, where materials that exhibit phosphorescence have the ability to absorb and store energy, which is then released as radiation for an extended period of time. For this reason, phosphorescent pigments have been applied in industrial uses. Further investigation is needed to develop pigments that could be longer lasting than the current ones.

The second section of the present work contains the literature review of luminescent polymers per se. Where different luminescence mechanisms are present for the various types of uses and applications that luminescent polymers can be applied on.

Aggregation-induced emission effect (AIE) is the precise opposite mechanism of the aggregation-caused quenching effect (ACQE). In concentrated liquids and in the solid phase, luminescent molecules have an innate predisposition for aggregation formation; to take advantage of the nature of these luminous molecules, some luminogens structures that present (AIE) have been created. With these molecules, it is intended that when a substance becomes aggregated, its luminous properties are enhanced. For instance, a great example of luminogens used for this intention is hexaphenylsilole (HPS). This characteristic of controllable 'turn on' by using AIE luminogens can lead to developing materials with potential for industry and real-world uses.

The major benefit of aggregation-induced emission luminogens over conventional aggregation-caused quenching fluorophores is the very efficient radiative transition in the aggregate state for practical implementations. Regardless of the remarkable success of aggregation-induced emission luminogens in basic research and practical applications, they nonetheless encounter obstacles. For instance, the emission characteristic of aggregationinduced emission luminogens is the most distinguishing property. When AIEgens are randomly packed, broad emission is often seen because the torsional structure and varying conformation might provide AIEgens with high energy levels, impacting the color accuracy of OLEDs.

In summary, this review provides a comprehensive and thorough examination of luminescent polymers that can be used in present times and future time technologies around the world. Finally, an improvement to this work will consist of analyzing and contrasting studies that allow us to distinguish in a better way the disadvantages of some mechanisms that luminescent polymers present, such as in AIE, in order to develop better technology, for example, in the field of OLEDs.

Abbreviations

PE Polyethylene

PP Polypropylene

PVC Polyvinyl chloride

PL Photoluminescence

EL Electroluminescence

ITO Indium tin oxide

CL Cathodoluminescence

TL Triboluminescence

NLPs Non-conjugated luminescent polymers

TPP Tripolyphosphate

MOFs metal-organic frameworks

CPs coordination polymers

PAMAM Poly(amido amine)

ACQ Aggregation-caused quenching

AIE Aggregation-induced emission

THF tetrahydrofuran

HPS Hexaphenylsilole

C-EE crosslink-enhanced emission

QY quantum yield

PEI Polyethyleneimine

LED light-emitting diode

LCD Liquid Cristal Display

TPE tetraphenylene

DSA distyrylanthracene

Bibliography

- E. Saldívar-Guerra and E. Vivaldo-Lima, "Introduction to Polymers and Polymer Types," *Handb. Polym. Synth. Charact. Process.*, pp. 1–14, 2013.
- [2] K. V. R. Murthy and H. S. Virk, "Luminescence phenomena: An introduction," *Defect Diffus. Forum*, vol. 347, pp. 1–34, 2014.
- [3] K. Bauri, B. Saha, A. Banerjee, and P. De, "Recent advances in the development and applications of nonconventional luminescent polymers," *Polym. Chem.*, vol. 11, no. 46, pp. 7293–7315, 2020.
- [4] D. Feldman, "Polymer history," *Des. Monomers Polym.*, vol. 11, no. 1, pp. 1–15, 2008.
- [5] D. Whelan, "Thermoplastic Elastomers," *Brydson's Plast. Mater. Eighth Ed.*, pp. 653–703, 2017.
- [6] S. Tao, S. Zhu, T. Feng, C. Zheng, and B. Yang, "Crosslink-Enhanced Emission Effect on Luminescence in Polymers: Advances and Perspectives," *Angew. Chemie*, vol. 132, no. 25, pp. 9910–9924, 2020.
- Q. Li, Y. Tang, W. Hu, and Z. Li, "Fluorescence of Nonaromatic Organic Systems and Room Temperature Phosphorescence of Organic Luminogens : The Intrinsic Principle and Recent Progress," *Small*, vol. 1801560, pp. 1–20, 2018.
- [8] R. S. Fontenot and W. A. Hollerman, "Triboluminescence theory, synthesi, and application," p. 454, 2016.
- [9] D. M. Jameson, "Introduction to fluorescence," in *Introduction to Fluorescence*, 2014, pp. 1–286.
- [10] P. J. Modreski and R. Aumente-Modreski, "Fluorescent Minerals," *Rocks Miner.*, vol. 71, no. 1, pp. 14–22, 1996.
- [11] B. Profiles, "Shining in the Niche Market with Luminous Pigment and IPRs Strategy," no. June, pp. 44–47, 2006.
- [12] B. Valeur and M. N. Berberan-Santos, "A brief history of fluorescence and phosphorescence before the emergence of quantum theory," *J. Chem. Educ.*, vol. 88, no. 6, pp. 731–738, 2011.
- [13] A. J. J. Bos, "Theory of thermoluminescence," *Radiat. Meas.*, vol. 41, no. SUPPL. 1, pp. 45–56, 2006.
- [14] H. Tugay, Z. Yegingil, T. Dogan, N. Nur, and N. Yazici, "The thermoluminescent properties of natural calcium fluoride for radiation dosimetry," *Nucl. Inst. Methods Phys. Res. B*, vol. 267, no. 23–24, pp.

3640-3651, 2009.

- [15] W. W. Piper and F. E. Williams, "Theory of electroluminescence," *Phys. Rev.*, vol. 98, no. 6, pp. 1809–1813, 1955.
- [16] C. Moretti, X. Tao, L. Koehl, and V. Koncar, "Electrochromic textile displays for personal communication," *Smart Text. Their Appl.*, pp. 539– 568, 2016.
- [17] G. Salviati, F. Fabbri, F. Detto, F. Rossi, L. Lazzarini, and T. Sekiguchi, "Cathodoluminescence of Self-assembled Nanosystems: The Cases of Tetrapods, Nanowires, and Nanocrystals," in *Characterization of Semiconductor Heterostructures and Nanostructures: Second Edition*, 2013, pp. 557–601.
- [18] J. Götze, "Application of cathodoluminescence microscopy and spectroscopy in geosciences," *Microsc. Microanal.*, vol. 18, no. 6, pp. 1270–1284, 2012.
- [19] D. H. J. Götze, M. Plötze, "Origin, spectral characteristics and practical applications of the cathodoluminescence (CL) of quartz - a review," *Mineral. Petrol.*, vol. 71, pp. 225–250, 2001.
- [20] T. Yanagida, "Inorganic scintillating materials and scintillation detectors," *Proc. Japan Acad. Ser. B Phys. Biol. Sci.*, vol. 94, no. 2, pp. 75–97, 2018.
- [21] C. S. & G. P. Justin Klein, "Radioluminescence in Biomedicine: Physics, Applications, and Models," *Med. Biol.*, pp. 0–23, 2018.
- [22] Thérèse Wilson and J. Woodland Hastings, "Bioluminescence," *Annu. Rev. Cell Dev. Biol*, pp. 197–230, 1998.
- [23] S. H. D. Haddock, M. A. Moline, and J. F. Case, "Bioluminescence in the sea," *Ann. Rev. Mar. Sci.*, vol. 2, no. 1, pp. 443–493, 2010.
- [24] R. J. Hoffman and L. S. Nelson, "Pediatric and young adult exposure to chemiluminescent glow sticks," *Arch. Pediatr. Adolesc. Med.*, vol. 156, no. 9, pp. 901–904, 2002.
- [25] M. Vacher *et al.*, "Chemi- and Bioluminescence of Cyclic Peroxides," *Chem. Rev.*, vol. 118, no. 15, pp. 6927–6974, 2018.
- [26] E. H. White and M. J. C. Harding, "Chemiluminescence in Liquid Solutions: the Chemiluminescence of Lophine and Its Derivatives," *Photochem. Photobiol.*, vol. 4, no. 6, pp. 1129–1155, 1965.
- [27] H. Kobayashi *et al.*, "Luminol-Dependent Chemiluminescence Assay," J. *Androl.*, vol. 22, no. 4, pp. 568–574, 2001.
- [28] J. Birriel and I. Birriel, "Glow Sticks: Spectra and Color Mixing," Phys.

Teach., vol. 52, no. 7, pp. 400–402, 2014.

- [29] J. I. Zink, "Triboluminescence," Acc. Chem. Res., vol. 11, no. 8, pp. 289–295, 1978.
- [30] I. B. Cohen and E. N. Harvey, "A History of Luminescence from the Earliest Times Until 1900," *Am. Hist. Rev.*, vol. 63, no. 4, p. 937, 1958.
- [31] J. T. Dickinson, L. B. Brix, and L. C. Jensen, "Electron and positive ion emission accompanying fracture of Wint-o-green Lifesavers and singlecrystal sucrose," *J. Phys. Chem.*, vol. 88, no. 9, pp. 1698–1701, 1984.
- [32] A. J. Walton, "Triboluminescence," Adv. Phys., vol. 26, no. 6, pp. 887– 948, 1977.
- [33] Z. Monette, A. K. Kasar, and P. L. Menezes, "Advances in triboluminescence and mechanoluminescence," J. Mater. Sci. Mater. Electron., vol. 30, no. 22, pp. 19675–19690, 2019.
- [34] N. Aich *et al.*, "Detection of crack formation and stress distribution for carbon fiber-reinforced polymer specimens through triboluminescentbased imaging," *J. Intell. Mater. Syst. Struct.*, vol. 26, no. 8, pp. 913–920, 2015.
- [35] N. Aich, A. Appalla, N. B. Saleh, and P. Ziehl, "Triboluminescence for distributed damage assessment in cement-based materials," *J. Intell. Mater. Syst. Struct.*, vol. 24, no. 14, pp. 1714–1721, 2013.
- [36] R. S. Fontenot, W. A. Hollerman, K. N. Bhat, M. D. Aggarwal, and B. G. Penn, "Incorporating strongly triboluminescent europium dibenzoylmethide triethylammonium into simple polymers," *Polym. J.*, vol. 46, no. 2, pp. 111–116, 2014.
- [37] J. Rooze, E. V. Rebrov, J. C. Schouten, and J. T. F. Keurentjes, "Dissolved gas and ultrasonic cavitation - A review," *Ultrason. Sonochem.*, vol. 20, no. 1, pp. 1–11, 2013.
- [38] K. S. Suslick, "Sonochemistry," no. March, 1990.
- [39] K. S. Suslick *et al.*, "Acoustic cavitation and its chemical consequences," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 357, no. 1751, pp. 335–353, 1999.
- [40] K. S. Suslick, "Sonoluminescence and sonochemistry," *Proc. IEEE Ultrason. Symp.*, vol. 1, pp. 523–532, 1997.
- [41] T. L. Stott and M. O. Wolf, "Electronic interactions in metallated polythiophenes: What can be learned from model complexes," *Coord. Chem. Rev.*, vol. 246, no. 1–2, pp. 89–101, 2003.

- [42] S. A. Chen, T. H. Jen, and H. H. Lu, "A review on the emitting species in conjugated polymers for photo-and electro-luminescence," *J. Chinese Chem. Soc.*, vol. 57, no. 3 B, pp. 439–458, 2010.
- [43] B. Xu and S. Holdcroft, "First observation of phosphorescence from .pi.conjugated polymers," J. Am. Chem. Soc., vol. 115, no. 18, pp. 8447– 8448, 1993.
- [44] F. I. Wu, P. I. Shih, C. F. Shu, Y. L. Tung, and Y. Chi, "Highly efficient light-emitting diodes based on fluorene copolymer consisting of triarylamine units in the main chain and oxadiazole pendent groups," *Macromolecules*, vol. 38, no. 22, pp. 9028–9036, 2005.
- [45] S. H. Jin, M. S. Jang, H. S. Suh, H. N. Cho, J. H. Lee, and Y. S. Gal, "Synthesis and characterization of highly luminescent asymmetric poly(pphenylene vinylene) derivatives for light-emitting diodes," *Chem. Mater.*, vol. 14, no. 2, pp. 643–650, 2002.
- [46] Z. Bao, A. J. Lovinger, and J. Brown, "New Air-Stable n -Channel Organic Thin Film Transistors," J. Am. Chem. Soc., vol. 7863, no. 23, pp. 207–208, 1998.
- [47] A. Nagai and Y. Chujo, "Luminescent organoboron conjugated polymers," *Chem. Lett.*, vol. 39, no. 5, pp. 430–435, 2010.
- [48] Y. Cui and S. Wang, "Diboron and triboron compounds based on linear and star-shaped conjugated ligands with 8-hydroxyquinolate functionality: Impact of intermolecular interaction and boron coordination on luminescence," J. Org. Chem., vol. 71, no. 17, pp. 6485–6496, 2006.
- [49] Q. Wu *et al.*, "Synthesis, structure, and electroluminescence of BR2q (R = Et, Ph, 2-naphthyl and q = 8-hydroxyquinolato)," *Chem. Mater.*, vol. 12, no. 1, pp. 79–83, 2000.
- [50] Y. Qin, C. Pagba, P. Piotrowiak, and F. Jäkle, "Luminescent organoboron quinolate polymers," J. Am. Chem. Soc., vol. 126, no. 22, pp. 7015–7018, 2004.
- [51] C. W. Tang and S. A. Vanslyke, "Organic electroluminescent diodes," *Appl. Phys. Lett.*, vol. 51, no. 12, pp. 913–915, 1987.
- [52] Z. Bao, J. A. Rogers, and H. E. Katz, "Printable organic and polymeric semiconducting materials and devices," *J. Mater. Chem.*, vol. 9, no. 9, pp. 1895–1904, 1999.
- [53] K. Tanaka and Y. Chujo, "Recent progress of optical functional nanomaterials based on organoboron complexes with β -diketonate, ketoiminate and diiminate," NPG Asia Mater., vol. 7, no. 11, pp. e223-15,

2015.

- [54] K. Ono *et al.*, "Synthesis and photoluminescence properties of BF2 complexes with 1,3-diketone ligands," *Tetrahedron*, vol. 63, no. 38, pp. 9354–9358, 2007.
- [55] G. Zhang, G. M. Palmer, M. W. Dewhirst, and C. L. Fraser, "A dualemissive-materials design concept enables tumour hypoxia imaging," *Nat. Mater.*, vol. 8, no. 9, pp. 747–751, 2009.
- [56] C. Goze, G. Ulrich, L. J. Mallon, B. D. Allen, A. Harriman, and R. Ziessel, "Synthesis and photophysical properties of borondipyrromethene dyes bearing aryl substituents at the boron center," *J. Am. Chem. Soc.*, vol. 128, no. 31, pp. 10231–10239, 2006.
- [57] O. García, L. Garrido, R. Sastre, A. Costela, and I. García-Moreno, "Synthetic strategies for hybrid materials to improve properties for optoelectronic applications," *Adv. Funct. Mater.*, vol. 18, no. 14, pp. 2017–2025, 2008.
- [58] R. D. Rieke and W. E. Rich, "Organic and Biological Chemistry," J. Am. *Chem. Soc.*, vol. 92, no. 25, pp. 7349–7353, 1970.
- [59] S. Polonsky and A. Weger, "Off-state luminescence in metal-oxidesemiconductor field-effect transistors and Its use as on-chip voltage probe," *Appl. Phys. Lett.*, vol. 85, no. 12, pp. 2390–2392, 2004.
- [60] J. C. Berrones-Reyes *et al.*, "Quantum chemical elucidation of the turn-on luminescence mechanism in two new Schiff bases as selective chemosensors of Zn2+: Synthesis, theory and bioimaging applications," *RSC Adv.*, vol. 9, no. 53, pp. 30778–30789, 2019.
- [61] W. F. Lai, "Non-conjugated polymers with intrinsic luminescence for drug delivery," *J. Drug Deliv. Sci. Technol.*, vol. 59, no. April, p. 101916, 2020.
- [62] M. P. Aldred *et al.*, "Fluorescence quenching and enhancement of vitrifiable oligofluorenes end-capped with tetraphenylethene," *J. Mater. Chem.*, vol. 22, no. 15, pp. 7515–7528, 2012.
- [63] K. T. Al-Jamal, P. Ruenraroengsak, N. Hartell, and A. T. Florence, "An intrinsically fluorescent dendrimer as a nanoprobe of cell transport," J. Drug Target., vol. 14, no. 6, pp. 405–412, 2006.
- [64] C. Cunha-Reis, K. Tuzlakoglu, E. Baas, Y. Yang, A. El Haj, and R. L. Reis, "Influence of porosity and fibre diameter on the degradation of chitosan fibre-mesh scaffolds and cell adhesion," *J. Mater. Sci. Mater. Med.*, vol. 18, no. 2, pp. 195–200, 2007.

- [65] K. Ma, X. Cai, Y. Zhou, Z. Zhang, T. Jiang, and Y. Wang, "Osteogenetic property of a biodegradable three-dimensional macroporous hydrogel coating on titanium implants fabricated via EPD," *Biomed. Mater.*, vol. 9, no. 1, 2014.
- [66] L. Wang *et al.*, "Establishing Gene Delivery Systems Based on Small-Sized Chitosan Nanoparticles," *J. Ocean Univ. China*, vol. 17, no. 5, pp. 1253–1260, 2018.
- [67] I. Alkorta and I. Rozas, "Non-conventional hydrogen bonds," *Chem. Soc. Rev.*, vol. 27, pp. 163–170, 1998.
- [68] S. W. Kuo, "Hydrogen-bonding in polymer blends," *J. Polym. Res.*, vol. 15, no. 6, pp. 459–486, 2008.
- [69] K. M. Hutchins, "Functional materials based on molecules with hydrogenbonding ability: applications to drug co-crystals and polymer complexes," *R. Soc. Open Sci.*, vol. 5, no. 180564, 2018.
- [70] S. H. Huang, Y. W. Chiang, and J. L. Hong, "Luminescent polymers and blends with hydrogen bond interactions," *Polym. Chem.*, vol. 6, no. 4, pp. 497–508, 2015.
- [71] M. Fazeli, J. P. Florez, and R. A. Simão, "Improvement in adhesion of cellulose fibers to the thermoplastic starch matrix by plasma treatment modification," *Compos. Part B Eng.*, vol. 163, pp. 207–216, 2019.
- [72] C. Wu and D. T. Chiu, "Highly fluorescent semiconducting polymer dots for biology and medicine," *Angew. Chemie - Int. Ed.*, vol. 52, no. 11, pp. 3086–3109, 2013.
- [73] S. Zhu, Y. Song, X. Zhao, J. Shao, J. Zhang, and B. Yang, "The photoluminescence mechanism in carbon dots (graphene quantum dots, carbon nanodots, and polymer dots): current state and future perspective," *Nano Res.*, vol. 8, no. 2, pp. 355–381, 2015.
- [74] J. Yu, Y. Rong, C. T. Kuo, X. H. Zhou, and D. T. Chiu, "Recent Advances in the Development of Highly Luminescent Semiconducting Polymer Dots and Nanoparticles for Biological Imaging and Medicine," *Anal. Chem.*, vol. 89, no. 1, pp. 42–56, 2017.
- [75] L. Guo, J. Ge, and P. Wang, "Polymer Dots as Effective Phototheranostic Agents," *Photochem. Photobiol.*, vol. 94, no. 5, pp. 916–934, 2018.
- [76] S. Liu *et al.*, "Hydrothermal treatment of grass: A low-cost, green route to nitrogen-doped, carbon-rich, photoluminescent polymer nanodots as an effective fluorescent sensing platform for label-free detection of Cu(II) ions," *Adv. Mater.*, vol. 24, no. 15, pp. 2037–2041, 2012.

- [77] P. Dorenbos, "Energy of the first 4f 7 →4f 6 5d transition of Eu 2+ in inorganic compounds," *J. Lumin.*, vol. 104, no. 4, pp. 239–260, 2003.
- [78] H. Terraschke and C. Wickleder, "UV, Blue, Green, Yellow, Red, and Small: Newest Developments on Eu2+-Doped Nanophosphors," *Chem. Rev.*, vol. 115, no. 20, pp. 11352–11378, 2015.
- [79] R. Gao, M. S. Kodaimati, and D. Yan, "Recent advances in persistent luminescence based on molecular hybrid materials," *Chem. Soc. Rev.*, vol. 50, no. 9, pp. 5564–5589, 2021.
- [80] B. Zhou, G. Xiao, and D. Yan, "Boosting Wide-Range Tunable Long-Afterglow in 1D Metal–Organic Halide Micro/Nanocrystals for Space/Time-Resolved Information Photonics," *Adv. Mater.*, vol. 33, no. 16, pp. 1–9, 2021.
- [81] J. Hao, X. Xu, H. Fei, L. Li, and B. Yan, "Functionalization of Metal– Organic Frameworks for Photoactive Materials," *Adv. Mater.*, vol. 30, no. 17, pp. 1–22, 2018.
- [82] Z. Yang *et al.*, "Intermolecular Electronic Coupling of Organic Units for Efficient Persistent Room-Temperature Phosphorescence," *Angew. Chemie*, vol. 128, no. 6, pp. 2221–2225, 2016.
- [83] X. Yang and D. Yan, "Strongly Enhanced Long-Lived Persistent Room Temperature Phosphorescence Based on the Formation of Metal–Organic Hybrids," *Adv. Opt. Mater.*, vol. 4, no. 6, pp. 897–905, 2016.
- [84] W. Zhang Yuan and Y. Zhang, "Nonconventional macromolecular luminogens with aggregation-induced emission characteristics," J. Polym. Sci. Part A Polym. Chem., vol. 55, no. 4, pp. 560–574, 2017.
- [85] I. Khan, K. Saeed, and I. Khan, "Nanoparticles: Properties, applications and toxicities," *Arab. J. Chem.*, vol. 12, no. 7, pp. 908–931, 2019.
- [86] D. A. Tomalia, B. Klajnert-Maculewicz, K. A. M. Johnson, H. F. Brinkman, A. Janaszewska, and D. M. Hedstrand, "Non-traditional intrinsic luminescence: inexplicable blue fluorescence observed for dendrimers, macromolecules and small molecular structures lacking traditional/conventional luminophores," *Prog. Polym. Sci.*, vol. 90, pp. 35–117, 2019.
- [87] S. Zhu, Y. Song, J. Shao, X. Zhao, and B. Yang, "Non-conjugated polymer dots with crosslink-enhanced emission in the absence of fluorophore units," *Angew. Chemie - Int. Ed.*, vol. 54, no. 49, pp. 14626– 14637, 2015.
- [88] P. Tomalia, D. A., Baker, H., Dewald, J., Hall, M., Kallos, G., Martin, S.,

... Smith, "A New Class of Polymers : Starburst-Dendritic," *Polym. J.*, vol. 17, no. I, pp. 117–132, 1985.

- [89] W. Y. Rui-bin Wang and X. Zhu, "Aggregation-induced Emission of Nonconjugated Poly (amido amine) s :," *Chinese J. Polym. Sci.*, vol. 33, no. 5, pp. 680–687, 2015.
- [90] C. L. Larson and S. A. Tucker, "Intrinsic Fluorescence of Carboxylate-Terminated Polyamido Amine Dendrimers," *Appl. Spectrosc.*, vol. 55, no. 6, pp. 679–683, 2001.
- [91] F. E. Williams and H. Eyring, "The mechanism of the luminescence of solids," *J. Chem. Phys.*, vol. 15, no. 5, pp. 289–304, 1947.
- [92] Y. Hong, J. W. Y. Lam, and B. Z. Tang, "Aggregation-induced emission: Phenomenon, mechanism and applications," *Chem. Commun.*, no. 29, pp. 4332–4353, 2009.
- [93] Y. Hong, J. W. Y. Lam, and B. Z. Tang, "Aggregation-induced emission," *Chem. Soc. Rev.*, vol. 40, no. 11, pp. 5361–5388, 2011.
- [94] D. Ding, K. Li, B. Liu, and B. Z. Tang, "Bioprobes based on AIE fluorogens," *Acc. Chem. Res.*, vol. 46, no. 11, pp. 2441–2453, 2013.
- [95] F. R. of G. Herbert Müller (retired), BASF Aktiengesellschaft, Ludwigshafen, "Tetrahydrofuran," Ullmann's encyclopedia of industrial chemistry. pp. 1–4, 2005.
- [96] J. B. Birks, "Excimers," *Reports Prog. physiscs*, vol. 38, no. 8, pp. 903– 974, 1975.
- [97] H. Huang *et al.*, "Aggregation caused quenching to aggregation induced emission transformation: a precise tuning based on BN-doped polycyclic aromatic hydrocarbons toward subcellular organelle specific imaging," *Chem. Sci.*, vol. 13, no. 11, pp. 3129–3139, 2022.
- [98] P. Yan, A. Chowdhury, M. W. Holman, and D. M. Adams, "Selforganized perylene diimide nanofibers," *J. Phys. Chem. B*, vol. 109, no. 2, pp. 724–730, 2005.
- [99] H. Wang, E. Zhao, J. W. Y. Lam, and B. Z. Tang, "AIE luminogens: emission brightened by aggregation," *Mater. Today*, vol. 18, no. 7, pp. 365–377, 2015.
- [100] U. Resch-genger and G. Hennrich, "Fluorescent Redox-Switchable Devices," *Top. Fluoresc. Spectrosc.*, pp. 189–218, 2007.
- [101] J. Wang *et al.*, "Alkyl and dendron substituted quinacridones: Synthesis, structures, and luminescent properties," *J. Phys. Chem. B*, vol. 111, no.

19, pp. 5082–5089, 2007.

- [102] B. Z. Tang, X. Zhan, G. Yu, P. P. Sze Lee, Y. Liu, and D. Zhu, "Efficient blue emission from siloles," *J. Mater. Chem.*, vol. 11, no. 12, pp. 2974– 2978, 2001.
- [103] J. Luo *et al.*, "Aggregation-induced emission of 1-methyl-1,2,3,4,5-pentaphenylsilole," *Chem. Commun.*, vol. 18, pp. 1740–1741, 2001.
- [104] S. Wang, B. Li, and F. Zhang, "Molecular Fluorophores for Deep-Tissue Bioimaging," ACS Cent. Sci., vol. 6, no. 8, pp. 1302–1316, 2020.
- [105] S. Dalapati, C. Gu, and D. Jiang, "Luminescent Porous Polymers Based on Aggregation-Induced Mechanism: Design, Synthesis and Functions," *Small*, vol. 12, no. 47, pp. 6513–6527, 2016.
- [106] Q. Peng, Y. Yi, Z. Shuai, and J. Shao, "Toward quantitative prediction of molecular fluorescence quantum efficiency: Role of Duschinsky rotation," *J. Am. Chem. Soc.*, vol. 129, no. 30, pp. 9333–9339, 2007.
- [107] S. Li, Q. Wang, Y. Qian, S. Wang, Y. Li, and G. Yang, "Understanding the pressure-induced emission enhancement for triple fluorescent compound with excited-state intramolecular proton transfer," *J. Phys. Chem. A*, vol. 111, no. 46, pp. 11793–11800, 2007.
- [108] X. Fan *et al.*, "Photoluminescence and electroluminescence of hexaphenylsilole are enhanced by pressurization in the solid state," *Chem. Commun.*, vol. 381, no. 26, pp. 2989–2991, 2008.
- [109] S. Zhu *et al.*, "The crosslink enhanced emission (CEE) in non-conjugated polymer dots: From the photoluminescence mechanism to the cellular uptake mechanism and internalization," *Chem. Commun.*, vol. 50, no. 89, pp. 13845–13848, 2014.
- [110] S. Tao, Y. Song, S. Zhu, J. Shao, and B. Yang, "A new type of polymer carbon dots with high quantum yield: From synthesis to investigation on fluorescence mechanism," *Polymer (Guildf)*., vol. 116, pp. 472–478, 2017.
- [111] T. Feng et al., "Supramolecular Cross-Link-Regulated Emission and Related Applications in Polymer Carbon Dots," ACS Appl. Mater. Interfaces, vol. 10, pp. 12262–12277, 2018.
- [112] M. Pope, H. P. Kallmann, and P. Magnante, "Electroluminescence in organic crystals [16]," *The Journal of Chemical Physics*, vol. 38, no. 8. pp. 2042–2043, 1963.
- [113] W. Helfrich and W. G. Schneider, "Recombination radiation in anthracene crystals," *Phys. Rev. Lett.*, vol. 14, no. 7, pp. 229–232, 1965.

- [114] C. Adachi, T. Tsutsui, and S. Saito, "Organic electroluminescent device having a hole conductor as an emitting layer," *Appl. Phys. Lett.*, vol. 1489, 1989.
- [115] D. X. Yu, "Light-Emitting Devices with Conjugated Polymers," pp. 1575– 1594, 2011.
- [116] B. Sim, C. K. Moon, K. H. Kim, and J. J. Kim, "Quantitative Analysis of the Efficiency of OLEDs," ACS Appl. Mater. Interfaces, vol. 8, no. 48, pp. 33010–33018, 2016.
- [117] B. Geffroy, P. le Roy, and C. Prat, "Organic light-emitting diode (OLED) technology: Materials, devices and display technologies," *Polym. Int.*, vol. 55, no. 6, pp. 572–582, 2006.
- [118] J. Chamorro, Pedro Martín, "Fundamentos de la tecnonolgía OLED," in Universidad de Valladolid. Escuela Técnica Superior de Ingenieros de Telecomunicación, 2008, p. 219.
- [119] G. Hong *et al.*, "A Brief History of OLEDs—Emitter Development and Industry Milestones," *Adv. Mater.*, vol. 33, no. 9, 2021.
- [120] J. Teresko, "Organic light emitting diode," *Ind. Week*, vol. 249, no. 20, p. 71, 2000.
- [121] Q. Ban, T. Bai, X. Duan, and J. Kong, "Noninvasive photothermal cancer therapy nanoplatforms: Via integrating nanomaterials and functional polymers," *Biomater. Sci.*, vol. 5, no. 2, pp. 190–210, 2017.
- [122] P. Cheng, J. Zhang, J. Huang, Q. Miao, C. Xu, and K. Pu, "Near-infrared fluorescence probes to detect reactive oxygen species for keloid diagnosis," *Chem. Sci.*, vol. 9, no. 30, pp. 6340–6347, 2018.
- [123] Y. Si *et al.*, "Fluorescent Copolymers for Bacterial Bioimaging and Viability Detection," ACS Sensors, vol. 5, no. 9, pp. 2843–2851, 2020.
- [124]Z. Lei *et al.*, "Stable, Wavelength-Tunable Fluorescent Dyes in the NIR-II Region for In Vivo High-Contrast Bioimaging and Multiplexed Biosensing," *Angew. Chemie*, vol. 131, no. 24, pp. 8250–8255, 2019.
- [125] L. Shen, "Functional Biomaterials Biocompatible Polymer / Quantum Dots Hybrid Materials : Current Status and Future Developments," J. Funct. Mater., vol. 2, pp. 355–372, 2011.
- [126] A. M. Derfus, W. C. W. Chan, and S. N. Bhatia, "Probing the Cytotoxicity of Semiconductor Quantum Dots," *Nano Lett.*, vol. 4, no. 1, pp. 11–18, 2004.
- [127] Y. Du, Y. Xue, P. X. Ma, X. Chen, and B. Lei, "Biodegradable,

Elastomeric , and Intrinsically Photoluminescent Poly (Silicon-Citrates) with high Photostability and Biocompatibility for Tissue Regeneration and Bioimaging," *Adv. Heal. care Mater.*, no. 5, pp. 382–392, 2016.

- [128] A. Reisch and A. S. Klymchenko, "Fluorescent Polymer Nanoparticles Based on Dyes: Seeking Brighter Tools for Bioimaging," *Small*, vol. 12, no. 15, pp. 1968–1992, 2016.
- [129] Q. Ban, Y. Li, and S. Wu, "Self-fluorescent polymers for bioimaging," *View*, vol. 3, no. 2, p. 135, 2021.
- [130] K. K. Yu, K. Li, J. T. Hou, J. Yang, Y. M. Xie, and X. Q. Yu, "Rhodamine based pH-sensitive 'intelligent' polymers as lysosome targeting probes and their imaging applications in vivo," *Polym. Chem.*, vol. 5, no. 19, pp. 5804–5812, 2014.
- [131] J. Qian and B. Z. Tang, "AIE Luminogens for Bioimaging and Theranostics: from Organelles to Animals," *Chem*, vol. 3, no. 1, pp. 56– 91, 2017.
- [132] C. Ma *et al.*, "Preparation of biocompatible aggregation-induced emission homopolymeric nanoparticles for cell imaging," *Macromol. Biosci.*, vol. 14, no. 2, pp. 235–243, 2014.
- [133] Y. Du, T. Bai, H. Yan, Y. Zhao, W. Feng, and W. Li, "A simple and convenient route to synthesize novel hyperbranched Poly(amine ester) with multicolored fluorescence," *Polymer (Guildf)*., vol. 185, p. 121771, 2019.
- [134] M. Sun, C. Y. Hong, and C. Y. Pan, "A unique aliphatic tertiary amine chromophore: Fluorescence, polymer structure, and application in cell imaging," J. Am. Chem. Soc., vol. 134, no. 51, pp. 20581–20584, 2012.
- [135] S. J. Tan, N. R. Jana, S. Gao, P. K. Patra, and J. Y. Ying, "Surface-Ligand-Dependent Cellular Interaction, Subcellular Localization, and Cytotoxicity of Polymer-Coated Quantum Dots," *Chem. Mater.*, vol. 22, no. 8, pp. 2239–2247, 2010.