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Synthesis, Characterization, and Applications of Carbon Dots: A Review

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Abstract: **Carbon dots (CDs) are small carbon-based nanoparticles that have gained significant attention in recent years due to their unique optical, electrical, and chemical properties. In this review, a comprehensive summary of the recent advances in the synthesis, characterization, and applications of CDs are provided. We discuss the different approaches for synthesizing CDs, including top-down and bottom-up strategies, and highlight the advantages and limitations of each method. We also review the various characterization techniques used to analyze the physical and chemical properties of CDs, such as transmission electron microscopy, Fourier transform infrared spectroscopy, and X-ray photoelectron spectroscopy. Furthermore, the applications of CDs in a range of fields, including bioimaging, sensing, catalysis, and energy conversion was discussed. The unique properties of CDs that make them attractive for these applications, such as their tunable emission spectra, biocompatibility, and excellent stability are also highlighted.**

Keywords: **Carbondot, top-down, bottom-up, photoluminescence, quantum yield.**

1. INTRODUCTION

Xu *et al*., [1] accidentally discovered carbon dots during the purification of single wall carbon nanotubes (SWCNTs). Two years after, Sun *et al*., [2], synthesized fluorescent carbon nanoparticles with diameter less than 10 nm, and named it carbon dots. Since then, carbon dots (CDs) have received much attention from researchers, due to their easy preparation, high photo luminescent properties, low cost, thermal stability, low toxicity, and easy functionalization [3]. These features have led to the wide application of carbon dots in bioimaging [4], sensors [5], photoluminiscent device [6], metal detection [7], drug delivery [8], [9] to mention but a few. CDs have been synthesized from different carbon precursors, using the top down and bottom up approaches [10], [11]. The top down method which include: laser ablation, arc discharge, acid oxidation, electrochemical synthesis etc. are used to cut down larger carbon materials to small sized fragments to form carbon dots [12]. Conversely, the bottom up method involves aggregating small carbon precursors to form carbon dots, through partial dehydration and dehydrogenation using microwave, solvothermal/hydrothermal pyrolysis, or thermal decomposition methods [13]. Many natural carbon precursors have been used for synthesis of CDs such as Kidney beans [14], sweet potato [15], peanut shells [16], almond husk [17], rice husk [18], and many others.

2. SYNTHESIS OF CARBON DOTS.

Carbon dots have been synthesized from different carbon precursors, using the top down and bottom up approaches [10], [11]. The top down method which include: laser ablation, arc discharge, acid oxidation, electrochemical synthesis, solvothermal/hydrothermal methods, are used to cut down larger carbon materials to small sized fragments to form carbon

dots [12]. Conversely, the bottom up method involves aggregating small carbon precursors to form carbon dots, through partial dehydration and dehydrogenation using microwave, solvothermal pyrolysis, or thermal decomposition methods [12].

Top-Down Method

1. Electrochemical Method

This method is used to synthesize carbon dots from larger carbon molecules such as graphite, carbon nanotubes, graphene, bio-char etc. [19], by an electrolytic process where the carbon molecule serves as electrodes in the presence of appropriate electrolyte. This method is the most common method for the synthesis of carbon dots with remarkable quality such as high yield, high purity, low cost and easy control over size [20]. Zhao and Xie [21] successfully synthesized CDs with polyaniline hybrid by an electrochemical technique. They prepared the CDs by electro-oxidation of graphite column electrode at 3.0V against a saturated calomel electrode in 0.1 M KH_2PO_4 aqueous solution as the supporting electrolyte.

2. Laser Ablation

This is a physical vapour deposition method in which a high power laser is used to vaporize a target carbon material heated at about 1200^{o}C inside a tube containing a metal catalyst in a helium or argon atmosphere [22], [23]. The carbon material is placed in a vacuum tube and irradiated with a focused laser beam. The heat generated on the irradiated target material makes it to sublime or evaporate into a plasma state, and further crystallizes to form nanoparticles. Laser ablation is a fast and effective method to prepare fluorescent CDs, however, its complicated mode of operation and cost limits its application. Sun *et al*. [2] were the first to produce CDs using laser ablation. In their work, a carbon source (baked graphite and cement) was irradiated with N.YAG 1064nm, 10Hz laser beam to produce carbon nanoparticles in aggregates of various sizes.

3. Arc Discharge

This method involves the use of two high purity graphite electrodes as anode and cathode held at short distance (~1-2 mm) apart in a helium atmosphere [24]. The electrodes are vaporized by the passage of a DC current (~100A) through the two electrodes in the presence of a metallic catalyst. The vapour forms carbon deposit on the chamber wall or over the cathode.

4. Chemical Oxidation

This is a method of carbon dots synthesis in which bulk carbon materials such as graphene or carbon nanotubes are subjected to chemical oxidation using strong oxidizing agents such as nitric acid, sulphuric acid, or hydrogen peroxide resulting in the formation of carbon dots with fluorescent properties [25]. This method is fast, easy to operate and has a high possibility for large scale production of CDs. However, its use is rare due to some of its major disadvantages which are (1) the highly corrosive nature of the chemicals and (2) causes pollution to the environment. Feng and Zhang [26] reported a simple and green synthesis of CDs via chemical oxidation of coke for application in lighting devices, using hydrogen peroxide as an oxidant. The as prepared CDs emitted blue fluorescence and had a florescence quantum yield of 9.2% and blue-green-red spectral composition of 48%.

5. Pyrolysis

This involves breaking down large carbon molecules to smaller particles of various sizes at a very high temperature. In this method, a carbon-rich material such as glucose, cellulose, or biomass is subjected to high temperatures in the absence of oxygen, resulting in the formation of CDs. The carbon-rich material is subjected to high temperatures (typically in the range of 500-800°C) in a reactor or furnace [27], [28]. The high temperature causes the carbon-rich material to break down into smaller pieces, resulting in the formation of CDs with fluorescent properties. The CDs are separated from the reaction solution by centrifugation or filtration. The size and fluorescence of the CDs can be controlled by adjusting the reaction conditions and the choice of carbon-rich material. Additionally, this method is a versatile and scalable method for synthesizing CDs. Praneerad *et al* [29] developed carbon dots of average size of about 10-30 nm from durian peel waste via pyrolysis. The obtained carbon dots were functionalized with fluorescent coumarin-6 dye for cell imaging.

Bottom-Up Method

1. Microwave Irradiation Method

Microwave assisted synthesis is a method for synthesizing carbon dots (CDs) by using microwave energy to generate heat, which can accelerate the breakdown of precursors and the formation of carbon dots [30]. The process involves mixing a precursor material, such as glucose or citric acid, with a metal salt, such as sodium citrate or cobalt nitrate, in a microwave-

safe container. The mixture is then subjected to microwave irradiation for a specified time, usually a few minutes, to produce CDs [31]. The microwave energy causes rapid heating and reaction of the precursor material, resulting in the formation of CDs with unique fluorescence and other optical properties. The reaction conditions, such as the type and amount of precursors, the solvent, and the microwave power, can be tailored to control the size, shape, and properties of the carbon dots. The method has been applied in a wide range of applications, including bioimaging, drug delivery, and energy storage, due to the unique optical and photothermal properties of carbon dots [32].

2. Hydrothermal/Solvothermal Method

These methods are the most widely used for the synthesis of carbon dots due to their low cost, environmental friendliness, and ease of operation [20]. In these methods, a solution of organic precursor is placed in a Teflon-lined autoclave where reaction occurs at a high temperature and pressure for several hours until the solution changes colour to brown, indicating the formation of CDs. Several reporters have synthesized CDs from various precursors using hydrothermal and solvothermal methods [33], [34]. In solvothermal method, organic solvents are used while in hydrothermal method, water is used as the solvent. Shen *et al*. [15] synthesized florescent carbon dots from sweet potato by hydrothermal method. The carbon dots prepared have an average size of 3.39nm with a quantum yield of 8.64%, and were used for detecting Fe^{3+} ion and for cell imaging. Hoan *et. al*. [35] synthesized CDs via a one-pot hydrothermal method from lemon juice. In their work, 40 mL lemon juice was extracted into a Teflon-lined stainless steel autoclave at 120ºC to 280ºC for 12 hours, until the solution turned dark brown indicating the formation of CDs. The as synthesized CDs exhibited strong luminescent properties and had potential applications in optoelectronics and bioimaging.

3. PHYSICO-CHEMICAL PROPERTIES OF CARBON DOTS

Carbon dots are small, carbon-based nanostructures with unique optical properties. They typically have a core of Sp^2-bonded carbon atoms surrounded by an outer shell of Sp^3-bonded carbon atoms and surface functional groups. Carbon dots are quasispherical or simply spherical in shape with sizes ranging from 1-10 nm [36], [37], and the sizes largely depend on the synthesis method and the precursors used. The surface functional groups, such as hydroxyl, carboxyl, and amine groups, determine the solubility and stability of the carbon dots in different solvents, as well as their compatibility with various biological systems. The fluorescence of carbon dots is usually due to the quantum confinement effect, where the small size of the carbon dot core leads to an increase in the energy of the fluorescent states and a corresponding red-shift in the emission spectra.

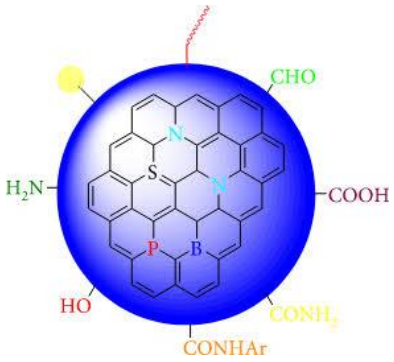

Figure 1: Generalized structure of CD (Gayen, 2019) [37]

4. OPTICAL PROPERTIES OF CARBON NANODOTS

Absorption

Generally, carbon dots exhibit strong absorption in the ultra violet (UV) region (230-320 nm) with a tail extending into the visible region of UV-VIS spectra. The absorption peaks of most carbon dots appear at about 249 nm -289 nm due to Π- Π* electronic transition of C=C bond and 300-350 nm due to n-Π* transition of C=O bonds [38], [35], [39]. It has been observed that CDs exhibit absorption irrespective of the synthesis method. For instance, Crista *et al*. [40], evaluated different bottom-up routes for the synthesis of carbon dots. They prepared three (3) types of CDs from the same set of precursors (urea and citric acid) via hydrothermal, micro-wave assisted, and calcination methods, and studied their optical properties. They observed that the absorption spectra of the three CDs are similar and showed absorption peaks at 245 nm and 350 nm, characteristics of Π- Π* transition of C=C bonds and n-Π* transition of C=O bonds respectively.

Photoluminescence

Photoluminescence (PL) occurs when light energy falls on a molecule, making it to absorb a photon leading to excitation of its electron to a higher electronic state, and then emits a photon as the electron returns to a ground state. It takes on three forms: fluorescence, phosphorescence, and chemiluminescence. Fluorescence occurs when a molecule on exposure to light energy emit light of longer wavelength. The colour of fluorescence depends on the wavelength of light emitted. The PL properties of carbon dots are determined using photoluminiscent spectroscopy and it is an important optical characteristic of carbon dots. PL of carbon dots depend on excitation wavelength (λ_{ex}), and as such multiple PL spectra can be obtained from a single carbon dots [37]. Generally, carbon dots commonly show PL maximum in the blue and green region of the spectra [41] and can be tuned by surface passivation and functionalization to meet desired applications. Increasing the excitation wavelength, increases the fluorescent intensity of carbon dots. For instance, Zhao *et al*. [42] reported an increase in fluorescence intensity of carbon dots prepared when the excitation wavelength shifted from 490 nm to 540 nm. Also Crista *et al*. [40], in their work reported the fluorescent properties of three (3) different carbon dots prepared from the same precursors. Their result showed that all three (3) carbon dots samples exhibited a blue fluorescence, and on increasing the excitation wavelength from 300 nm to 440 nm, a red shift toward green emission was observed. Although most carbon dots exhibit wavelength excitation dependent fluorescence behavior, some show excitation independent fluorescence characteristics [43]. For instance, Feng *et al*. [43] prepared microwave assisted nitrogen rich carbon dots (N-CDs) which showed excitation independent fluorescent characteristic. They attributed this behavior to less surface defects and more uniform sizes of the N-CDs.

Upconversion Photoluminescence

Up-conversion photoluminescence (UPCL) is a very important optical property of carbon dots, which makes them find wide application in bio-imaging [44], [37]. UPCL is a process that involves absorption of multi-photons (two or more photons) simultaneously resulting in the emission of light at a shorter wavelength than the excitation wavelength. Typically, carbon dots exhibit UPCL in the range of 325 nm to 425 nm when excited at a longer wavelength from 500 nm to 1000 nm. Cao *et al*. [45] first reported that when carbon dots are irradiated by a femtosecond pulsed laser for two-photon excitation in the near infra-red range (800-840 nm) or by an argon-ion laser (458 nm), they exhibited strong emission in the visible region. Cui *et al*. [46] prepared carbon dots from ammonium citrate and hydrogen peroxide as precursors in aqueous solution through hydrothermal process. The CDs showed excellent up-conversion property and were used for HeLa cell imaging. Recently, Deng *et al*. [47] prepared carbon dots (CDs) with up-conversion fluorescence behavior for enhancement of the photocatalytic activity of titanium oxide. The CDs were excited with light of 560 nm to 760 nm, the UPCL spectra of the CDs appeared from 300 nm to 550 nm with the strongest emission peak located at 350 nm with an excitation wavelength of 600 nm. They attributed the behavior of the CDs to multi-photon active process where multiple photons were simultaneously absorbed and emitting light of shorter wavelength.

5. QUANTUM YIELD (QY) OF CARBON DOTS

Quantum yield (QY) of carbon dots can be determined by UV-Vis and PL spectroscopy. It is determined by comparing the quantum yield of the carbon dots with that of quinine sulphate as the reference. The PL spectra of the quinine sulphate solution and carbon dots with identical UV absorbance at the same wavelength excitation are recorded. Thus, a simple ratio of integrated PL intensity of the two solutions will give the QY of the carbon dots [48], [26].

CHARACTERIZATION OF NANOMATERIALS

The characterization techniques for carbon dots are segmented into morphological, structural characterizations, and optical characterization. Various microscopic and diffraction techniques are employed for the morphology, size, structural, and optical characterization of carbon dots.

orphological characterization

There are several tools that have been used by researchers for determining the morphology and particle size of CDs of which scanning electron microscope (SEM) and transmission electron microscope (TEM) are the most frequently used. They provide information about the morphology, particle size, topography and size distribution of nanomaterials [49].

Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is a useful tool for determining the morphology, size distribution, and particle size of CDs [49]. It works by focusing a beam of electrons on the carbon dots sample and scans it in a raster pattern along x- or y-axis. When the electrons hit the sample, they interact with the sample and create a number of signals in the form of secondary

electrons (SEs), backscattered electrons (BSEs) and characteristic x-rays. The secondary electrons, backscattered electrons and the characteristic x-rays are detected by specialized detectors which then create images which are displayed on a computer screen. SEM results of carbon dots from various researchers have showed that they are spherical in shape.

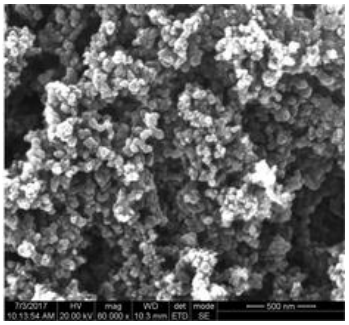

Figure 2: SEM image of CDs (source: [50])

Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) gives a 2D image of carbon dots sample by focusing a very high electron beam onto it. When electron beam strikes the sample, it interacts with it and some are reflected, scattered, or transmitted. An objective lens focuses the transmitted beam of electrons to form a bright field image which passes down to a projector lens for magnification. The magnified image strikes a detector screen where it is seen or recorded by a digital camera. Like SEM, TEM results of carbon dots prepared from different precursors have also showed they are spherical in shape with diameters ranging from 2-50 nm. [14], [15].

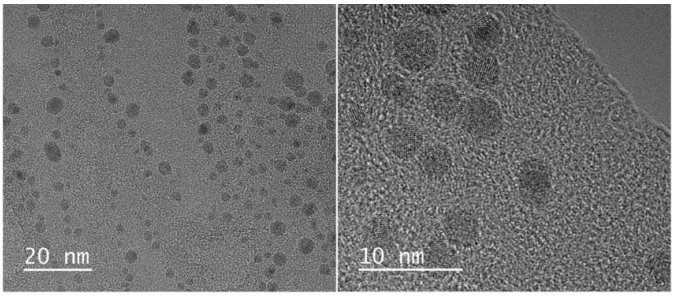

Figure 3: TEM images of carbon dots derived from banana peels (Source: [51])

High Resolution Transmission Electron Microscopy (HRTEM)

Recently, researchers have extensively used high resolution transmission microscope (HRTEM) to obtain a high resolution image of carbon dots [52]. It is a powerful technique for characterizing the structure and morphology of CDs. It is a type of transmission electron microscopy imaging based on the principle of electron diffraction, where a beam of electrons is directed at a thin sample, and the electrons that pass through the sample are diffracted, forming a diffraction pattern on a detector. In HRTEM, the sample is typically prepared by embedding the nanoparticles in a thin film of amorphous carbon or gold, and then thinning the sample using a technique called electron beam thinning. This results in a thin film of the CDs that is only a few nanometers thick, which allows the electrons to pass through the sample without significant scatter. The main advantage of HRTEM is its high resolution, which allows for the visualization of atomic-scale details in the CDs.

Atomic Force Microscopy

Atomic force microscopy (AFM) is a non-destructive high resolution non-optical imaging technique capable of producing a high resolution two-dimensional and three-dimensional images of CDs [49], [53]. Unlike SEM and TEM, AFM is a scanning probe microscopy which uses a probe to measure the topography of the sample. It works by measuring the forces that interact between a fine probe and the sample. The probe has a sharp tip and is attached to the end of a silicon or silicon nitride cantilever. The cantilever is deflected by the attractive or repulsive forces between the tip and the sample surface as the AFM scans the sample surface in a raster pattern. A laser beam that reflects on the cantilever's back side measures the bending. Finally, the forces are calculated by combining the laser data and is further detected by a photodetector. AFM has the advantage of not requiring any surface preparation or coating prior to imaging. As a result, the topographical analysis of CDs can be carried out using AFM without any special treatment [54].

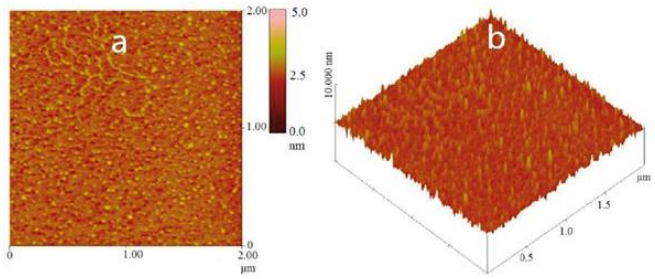

Figure 4: AFM image of CDs in a 3-dimensional (a) and 2-dimensional view (Source: Hua *et al*., 2015) [55]

STRUCTURAL CHARACTERIZATION

The structural properties of nanoparticles are critical for understanding the composition and nature of bonding materials. It provides various details about the bulk properties of the nanomaterial. The most common techniques used to investigate the structural properties of NPs are X-ray diffraction (XRD), energy dispersive X-ray (EDX), X-ray photoelectron spectroscopy (XPS), Raman, Brunauer - Emmett- Teller (BET) surface area analysis, and Zeta size analyzer, Fourier Infrared Spectroscopy (FT-IR).

X-ray Diffraction (XRD)

X-ray diffraction (XRD) is a versatile technique used in nanotechnology to characterize and obtain accurate information about the composition, crystal structure, and crystalline grain size of CDs based on their diffraction pattern [56], [57]. XRD operates on the basis of Bragg's law, which states that ($n\lambda = 2d\sin\theta$), where, λ, d, and θ denote the X-ray wavelength, interatomic plane spacing, and angle of incidence respectively. In its working, a beam of X-ray is passed through the nanoparticle sample, and is scattered, or diffracted, by the atoms in the X-rays' path. The interference caused by the X-ray scattering is observed using Bragg's law, coupled with a suitable detector to determine the crystalline structure characteristics of the CDs sample. As a result, information regarding the sample's crystal defects, crystal size, crystalline phase, shape anisotropy, strain, texture can be obtained from the evaluation of the diffraction peaks' width, shape, and position [53].

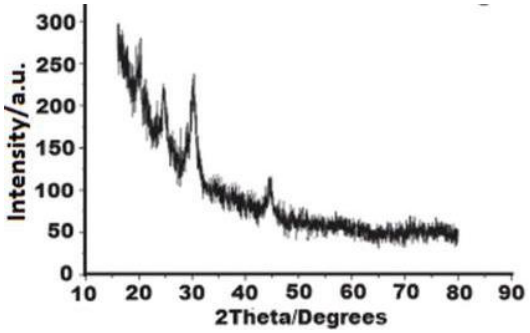

Figure 5: XRD pattern of CD (source: Pandey [58])

Energy Dispersive X-Ray Spectroscopy (EDX)

EDX is an analytical technique used for the elemental analysis or chemical characterization of CDs [59], [39]. It is a type of X-ray spectroscopy that uses a beam of X-rays to excite the electrons in the CDs, causing them to emit X-ray fluorescence. The energy of the emitted X-rays is then measured and used to identify the elements present in the CDs sample. EDX can be used for qualitative as well as quantitative analysis [53]. The basic principle of EDX is that different elements have unique X-ray emissions, which allows the identification of the elements present in a sample. One advantage of EDX is it can be used in conjunction with a microscope, such as a scanning electron microscope (SEM) or a transmission electron microscope (TEM), to obtain detailed information about the chemical composition of the CDs at a specific location.

Fourier Transform Infrared Spectroscopy (FT-IR)

Fourier Transform Infrared (FTIR) Spectroscopy is a technique used to identify and analyze the chemical composition of CDs [60] by measuring its infrared (IR) absorption spectrum. The sample is irradiated with a broad spectrum of IR radiation, and the absorption of specific wavelengths is measured. The resulting absorption spectrum can then be analyzed using a mathematical technique called a Fourier Transform to identify the specific chemical bonds [61] present in the sample.

OPTICAL CHARACTERIZATION

Optical characterization provides information about the absorption, reflectance, and photoluminescent properties of CDs. CDs, due to their distinct colors exhibit optical properties which can be determined with ultraviolet-visible (UV-Vis) spectroscopy, and photoluminescent spectroscopy [53].

Ultraviolet-Visible (UV-Vis) Spectroscopy

UV-Vis spectroscopy is based on Beer-Lamberts law, and measures the amount of light absorbed and scattered by a sample (a quantity known as extinction, which is defined as the sum of absorbed and scattered light). CDs have unique optical properties that are sensitive to the size, shape, concentration, agglomeration state, and refractive index near their surface, which makes UV-Vis spectroscopy a valuable tool for identifying, characterizing, and studying CDs [62]. Carbon dots exhibit fluorescence in the UV region of the electromagnetic spectrum with a tail extending to the visible region [15], and researchers have shown that most carbon dots exhibit wavelength excitation (λ_{ex}) dependent fluorescence [63], [37], [40], [64].

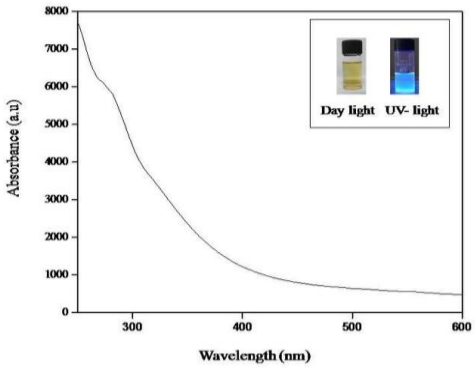

Figure 6: UV-Vis Spectrum of carbon dot obtained from sugar molasses (Source: [65])

Photoluminescent spectroscopy (PL)

This is a technique used to study the properties of a material by measuring the light emitted by the material when it is excited by a specific type of energy. The emitted light is typically in the visible or ultraviolet range and is used to determine the properties of the material, such as its composition, structure, and defects. It is a powerful tool for analyzing the electronic and optical properties of nanomaterials [62]. The working principle of photoluminescent spectroscopy is based on the phenomenon of photoluminescence, in which a material absorbs energy and subsequently emits light. The process begins by illuminating the sample with a light source that excites the material's electrons to a higher energy state. These excited electrons then relax back to their ground state, releasing the energy they absorbed in the form of light. This emitted light can be collected and analyzed to determine the properties of the material. The light is then detected by a detector, such as a photomultiplier tube or a charge-coupled device (CCD) camera. The data collected by the detector is then used to create a photoluminescent spectrum, which is a plot of the intensity of the emitted light as a function of wavelength. Carbon dots has been shown to exhibit PL maximum in the blue and green region of the spectra [41]. The photoluminescent spectrum can be used to determine the properties of CDs, such as its composition, structure, and defects.

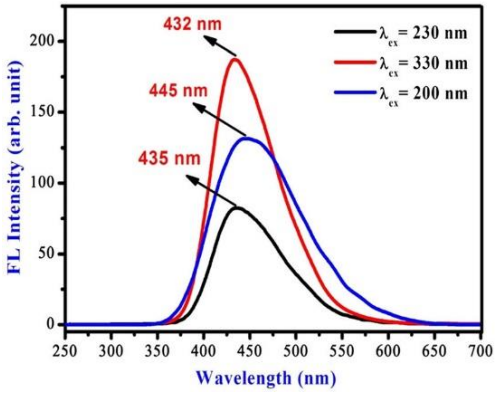

Figure 7: Fluorescence emission spectra of CDs at different wavelength (source: [66])

APPLICATIONS OF CARBON DOTS

Drug-Delivery

Due to photoluminescence, low toxicity, and biocompatibility, carbon dots have gained wide application in drug delivery for treatment of cancer. Most chemotherapy drugs have poor solubility in water, non-biocompatible and toxic to normal cells [67], and these limit their medical applications. To address these, draw backs, carbon dots have been used as nanocarriers to deliver anti-tumor drugs to cancer cells. Some workers have reported combining carbon dots with Doxorubicin (DOX), an anti-tumor drug for its proper delivery into cancer cells. Kong *et al.* [8], synthesized carbon dots via hydrothermal method from citric acid and ethylene diamine. The prepared carbon dots were conjugated with Doxorubicin to form CDs-DOX complex.

Bio-Imaging

Carbon dots have received a lot of attention in recent years due to their bright and stable fluorescence, small size, low toxicity, and biocompatibility, making them attractive for use as fluorescent probes in bioimaging. Most organic and inorganic dyes used for cell imaging are toxic to living cells and also require cell fixation which limit their use [67]. To resolve this, carbon dots have been used extensively as fluorescent probes for cell imaging. A study carried out by Architha *et al*. [68] described the development of carbon dots for bioimaging applications. The authors synthesized CDs from *Plectranthus amboinicus* (Mexican mint leaves) and demonstrated their use as fluorescent probes in cell imaging. The study highlighted the potential of carbon dots as a promising tool for various bioimaging applications. Also Edison *et al*. [69] demonstrated the use of carbon dots as a fluorescent staining agent for cell imaging of candida albican with low toxicity.

Sensing Application

Carbon dots have been extensively used by researchers for sensing different analytes, such as metal ions, anions, bacteria, and small molecules. The sensing applications of carbon dots can be attributed to the functional groups on the surface of carbon dots, enabling them to interact with the various analytes [70], [71]. The sensitivity and selectivity of metal ions to carbon dots vary depending on the binding affinity of the surface functional groups of the carbon dots toward a specific metal ion [72]. The surface of carbon dots contains phenolic hydroxyl, carboxylic, and amine functional groups, which can form coordinate bond with metal ions leading to fluorescent quenching [69] [73]. Fluorescent quenching occurs when the excited electrons of the carbon dots instead of returning to the ground state and generate fluorescence, undergo non-radiative electron transfer to the unfilled orbitals of the metal ions. Many workers have reported the application of carbon dots for sensing metal ions such as Fe^{3+}, Hg^{2+}, Ag^{+}, Pb^{2+}, Cu^{2+}, Au^{3+}, Cr^{6+} etc.

Water Purification

Carbon dots have been applied for water purification due to their photocatalytic properties, and this is a growing area of research with the goal of improving water quality and reducing environmental pollution [74]. Carbon dots are used as photocatalyst for degrading organic pollutants in water. Photocatalytic degradation is a process in which the carbon dots, is used to accelerate the breakdown of pollutants under the influence of light. This process can be used to remove contaminants such as dyes and pharmaceuticals from water. Das *et al*. [75] used bare carbon dots solvothermally synthesized from pear juice for the photocatalytic degradation of methylene blue (MB) dye. The photocatalytic efficiency of carbon dots can be enhanced by modifying their electronic structure in any of the following ways which include: metal ion doping, heteroatom doping, metal oxide composite formation [34], [76]. Peng *et al*. [77] used boron doped carbon dots as efficient catalyst for rhodamine B (RhB) and methylene blue (MB) degradation from water. The combination of carbon dots with metal oxides such as TiO_2, ZnO, and SiO_2 extends absorption of photons into the UV region. The role of the carbon dots is to (1) absorb visible light with long wavelength and then emit short wavelength photons on relaxation to induce photoexcitation of the metal oxide, resulting in the generation of electron-hole pairs, to liberate reactive oxygen species that consequently causes redox reaction. (2) To facilitate electron transfer from the metal oxide surface after photoexcitation to promote charge separation and charge transfer for photocatalytic reactions [78]. Atchudan *et al.* [79] investigated the photocatalytic efficiency of TiO_2 and nitrogen doped carbon dots nanocomposite (TiO_2/N-CDs) in the degradation of MB under UV irradiation. They recorded 90% degradation efficiency of the TiO_2/N-CDs composite within 40 minutes, with a rate constant 5 times higher than that of bare TiO_2 nanoparticles.

Solar Cells

The use of carbon dots in solar cells is a relatively new field of research, with the goal of improving the efficiency and performance of solar cells. Carbon dots have unique optical and electronic properties, including strong light absorption, high photoluminescence, and efficient electron transfer, which make them a promising candidate for use in solar cells.

Carbon dots can be used as electron-accepting materials in solar cells, and as sensitizers in dye-sensitized solar cells [80]. A recent study by [81] demonstrated the use of carbon dots as electron-accepting materials in perovskite solar cells, showing improved performance and efficiency compared to traditional materials.

6. CONCLUSION

Carbon dots (C-dots) have emerged as a promising class of carbon-based nanomaterials with diverse applications in various fields. The synthesis of C-dots is relatively simple, cost-effective, and environmentally friendly, making them an attractive alternative to traditional semiconductor quantum dots. The characterization techniques used to analyze C-dots have advanced significantly in recent years, allowing for a better understanding of their properties, such as size, shape, surface charge, and optical properties. Moreover, the unique optical properties of C-dots, such as their tunable fluorescence, make them ideal candidates for bioimaging, biosensing, drug delivery, and optoelectronic applications.

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