Environmental and toxicological assessment of nanodiamond-like materials derived from carbonaceous aerosols

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**Highlights**

- We demonstrate the conversion of carbonaceous aerosols to valuable nanodiamonds.
- The nanodiamonds produced are biocompatible and safe for bio-application.
- Blue-fluorescence of NDs observed is excitation dependent.

**Graphical Abstract**

**Abstract**

Carbonaceous aerosols (CAs) are ubiquitous and among the most significant environmental materials found in ambient air, mainly derived from anthropogenic sources (biomass burning, industrial activity, vehicle emissions, etc.). Elemental carbon (black carbon) and organic carbons are the major constituents of CAs. Due to their toxic effects, they are considered as high-risk compounds for human health. The key objective of the present work is to conduct a feasibility study for the conversion of CAs (TSP and PM\textsubscript{10}) into a value-added carbon nanostructured product by using a chemical method. High resolution-transmission electron microscopy (HR-TEM), X-ray diffraction (XRD), Raman spectroscopy, Fourier transforms infrared spectroscopy (FT-IR), X-ray photoelectron spectrometer (XPS), ultraviolet–visible spectroscopy (UV–visible), fluorescence spectroscopy (FL), and Zeta potential analyses indicated the formation of carbon nanomaterials with crystalline phases, which exhibit the characteristics of nanodiamonds (NDs). The HR-TEM image analysis showed that the nominal size of the CAs-derived NDs ranged from 4 to 17 nm composed of mainly carbon and oxygen. The FT-IR and XPS analysis indicated that the NDs are highly functionalized with an oxygen-containing functional group. The CAs-derived NDs showed the property of blue-fluorescence with excitation dependent. In the cytotoxicity and genotoxicity study, the NDs obtained was observed to be biocompatible and suitable for bioimaging applications. This result provides a new avenue for the conversion of CAs to high-value products leading to the mitigation of atmospheric pollution.

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**Keywords:** Carbonaceous aerosols (CAs), Value addition, Nanodiamonds (NDs), Cytotoxicity, Genotoxicity

**Article History:**
Received 12 March 2019
Received in revised form 24 April 2019
Accepted 30 April 2019
Available online 02 May 2019

Editor: Pavlos Kassomenos

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DOI: 10.1016/j.scitotenv.2019.04.446
1. Introduction

Carbonaceous aerosols (CAs) are solid or liquid particles that are suspended in the atmosphere. They are categorized into different categories depending on their size, such as coarse (PM10 or <10 μm), fine (PM2.5, or 2.5 μm), and total suspended particulate (TSP) matter (Islam et al., 2019; Saikia et al., 2016a, 2016b). Carbon compounds are generally referred to as carbonaceous aerosol including dust particulates. CAs suspended in the atmosphere have received increased attention worldwide due to their adverse impacts on both, human health and climate. CAs mainly constitute elemental carbon (black carbon) that accounts for a fraction of particulate matter (PM) (Putaud et al., 2004) and organic carbon which is a mixture of oxygenated compounds or hydrocarbon (PAHs, VOCs), elemental carbon (EC), organic carbon (OC), and metal compounds. Several studies have reported various impacts of CAs all over India. In industrialized and polluted suburban areas, 20% total suspended particles and polluted suburban areas up to 80% fine particles in the atmosphere are found to be in the form of carbonaceous species (Nunes and Pio, 1993; Parashara et al., 2005). The dark constituents of CAs are known as black carbon or soot particles generated mainly from anthropogenic sources, and are considered as light absorbing particles or include organic matter as well as a mixture of particles like graphite (Parashara et al., 2005; Andreea and Merlet, 2001). The latter contribute to atmospheric pollution, thus leading to climate change and human health risk.

Several researchers have reported the environmental and toxicological assessment of aerosols (Yadav et al., 2018; Saikia et al., 2016a, b). Some studies have also established the presence of carbon nanoparticles like fullerene, carbon nanotubes in atmospheric aerosols (Saikia et al., 2016a, b; Polk et al., 2016; Tsai et al., 2009). Zhu et al. (2012) for the first time reported the presence of a high amount of nanodiamonds in an explosion smoke. However, as per the literature survey, no detailed work has been carried out on the fabrication of carbon nanomaterials from CAs. Till now, the aerosol samples have been only characterized in order to assess its environmental effects. Therefore, there is a possibility to utilize the abundantly available carbon in CAs for the fabrication of carbon nanomaterials leading to its environmental mitigation.

In the present investigation, for the first time, we report the chemical fabrication of nanodiamonds (NDs) from the atmospheric CAs. In recent years, carbon nanoparticles such as nanodiamonds have increased worldwide attention due to their medical applications such as drug delivery, bio-sensing, and biomedical imaging. NDs occur in a form of diamond phase along with a cluster of carbon which includes nanocarbons (amorphous), graphite, fullerene nanodiamonds, and carbon nanotubes (Das and Saikia, 2017; Schrand, 2009; Schrand et al., 2009, Mochalin et al., 2012). NDs are also used in metal coating, lubricant additives, and novel wear resistant polymer due to the presence of abrasive nature, super hardness properties, and high chemical resistivity, respectively (Nunn et al., 2017). Fluorescence stability, chemical inertness, biocompatibility, and biosafety are the major characteristics of NDs. They have optical properties, higher electrical resistance, better conductivity of heat, and are also transparent to visible light, ultraviolet radiation, infra-red, and X-ray. The synthesis of nanodiamond was first studied in Russia in the mid-year of 1950 (Das and Saikia, 2017). ND is a particle which consists of a single-crystal diamond kernel within a shell containing functional groups. The first artificial nanodiamonds were synthesized by detonating carbon-containing explosives in absence of oxygen environment (Das and Saikia, 2017). Since then, many other methods have been discovered to produce nanodiamond such as HPHT (high energy ball milling of high-pressure high-temperature) diamond microcrystals, RDX (research department explosive), CVD (chemical vapor deposition) (Kazi, 2014), laser ablation, microplasma-assisted technique in presence of ethanol vapor at atmospheric pressure, chlorination of carbides, electron irradiation of carbon onions, ion irradiation of graphite and ultrasound cavitation (Nunn et al., 2017). Schrand (2009) reported the synthesis of detonation nanodiamond (DND) or ultradisperser diamond (UDD) with a sizes range of 4–5 nm by the detonation of explosives carbon particle.

In the course of our study, the main novelty is the fabrication of NDs from CAs, which leads to the formation of value-added product and possible mitigation of atmospheric pollution. Here, CAs were utilized to fabricate NDs by using a typical oxidative chemical technique. However, this experiment was very challenging due to the presence of toxic compounds associated with CAs. Therefore, efforts were also put into this investigation to separate and remove the toxic metals, organic compounds, and atmospheric impurities by using different laboratory scale technique as reported elsewhere (Kumar et al., 2015; Das and Saikia, 2017). To established the fabrication NDs from CAs, advanced level characterization techniques such as High resolution transmission electron microscopy (HR-TEM), Fourier transforms infrared (FT-IR) spectroscopy, X-ray photoelectron spectroscopy (XPS), ultraviolet-visible spectroscopy (UV-visible), Fluorescence spectroscopy (FL), X-ray diffraction (XRD), Raman spectroscopy, and Zeta potential were used. Moreover, the cytotoxicity and genotoxicity assays were performed to determine the toxicity of NDs for possible biological applications.

2. Experimental sections

2.1. Collection of carbonaceous aerosols (CAs) samples and fabrication of NDs

The carbonaceous aerosol samples (TSP and PM10) were collected by using a High Volume Sampler (Envirotech) and Respirable Dust Sampler (Envirotech, APM-460 NL) on pre-weighed filter papers (GF/A filters) around CSIR-NEIST campus, Jorhat (Northeastern region of India). The sampling of TSP and PM10 was conducted for 8 h daily during 21 and 7 days, respectively. During sampling periods, the average temperature was found to be 21 °C with an average wind speed of 1.6 m/s. The study area is shown in Fig. 1. Following the sampling procedure (CPCB, 2011), the filter papers were kept in a desiccator for further characterizations and experiments.

The collected CAs samples (TSP) are denoted as P1, P2, and P3 for the 1st week, 2nd week, and 3rd week, respectively. Another CAs sample (PM10) is denoted as P4. For the fabrication of NDs, 6 g of each CAs samples (TSP and PM10) was mixed with 100 mL of hydrogen peroxide (30%) in a Teflon beaker and the mixture was then ultrasonicated (frequency: 20 kHz) in microprocessor-based ultrasonicator (Model-Power Sonic520) for about 1 h at an atmospheric pressure and temperature as reported elsewhere (Das and Saikia, 2017). Polytetrafluoroethylene membrane filter (0.22 μm) was used to filtrate the resultant mixture. The mixture was then centrifuged (Eppendorf; Centrifuge 5430) at 1400 rpm for 1 h (Steinhil et al., 2015). The supernatant was carefully taken and treated with nitric acid to remove the atmospheric contaminants or impurities (Krüger et al., 2005). The nitric acid treated supernatants were then concentrated using rotary evaporator. The rotary evaporated supernatant products obtained from the P1, P2, P3, and P4 are denoted as S1, S2, S3, and S4, respectively and kept in a refrigerator at 4 °C for subsequent analysis. To evaluate the combined toxicity of NDs, one representative sample (S5) was also prepared by mixing equal amounts of S1, S2, S3, and S4.

2.2. Characterization techniques of NDs

The High-resolution transmission electron microscope (HRTEM) and energy dispersive X-ray spectroscopy (EDS) analysis was performed by using JEOL JEM 2100, resolution: 1.9 to 1.4 Å, worked at an accelerating voltage: 60–200 kV, for analysis, dispersed representative colloidal solutions of S1, S2, S3, and S4 were prepared and drop casted onto carbon-coated standard copper grids which were kept in a
IR) analysis of aerosol samples was performed in an FTIR (System-Model LabRam HR). The Fourier Transform Infrared spectroscopic (FT-IR) analysis of aerosol samples was performed in an FTIR spectrometer (Make: Horiba Jobin Vyon). The Raman analysis was also recorded in an ultraviolet–visible spectrophotometer (Analytik Jena, SPECORD200, Germany) and fluorescence (FL) spectra were recorded in fluorescence spectrophotometer (Horiba Fluorolog-3). The surface charge analysis of NDs was determined by using ZETASIZER (Model- Nano ZS, Malvern, UK).

2.3. Cell culture and treatment with NDs

The normal kidney epithelial (NKE) cell line was obtained from Prof Parames C. Sil, Bose Institute, Kolkata, India. Cells were sustained in RPMI medium improved with 10% fetal bovine serum (FBS) and antibiotics at 37 °C in culture flasks with 5% CO₂. Confluent monolayers (80%) of NKE cells were subjected to exposure of produced NDs at a dose of 5, 10, 20, 50, 100, 150, and 200 μg/mL for 24 h.

2.4. Cytotoxicity assay of NDs

Cytotoxicity was determined by using the Alamar Blue reduction bioassay (Alamar Biosciences, Sacramento, CA) (Manna and Jain, 2011). This method is based upon Alamar Blue dye reduction by live cells. After treatment with the produced NDs, the treatment medium was aspirated and 200 μL of Alamar Blue solution was added to each well and further incubated for 4 h at 37 °C. The optical density of each well was measured by using a microplate reader with absorbance at 570 and 600 nm. Similar conditions were repeated three times and the well without any treatment was taken as a control. The results were expressed as a percentage over control.

2.5. Genotoxicity or DNA fragmentation assay of NDs

The extent of genotoxicity or fragmentation of DNA was assayed in genomic DNA samples with the help of electrophoresis technique, isolated from control as well as NDs treated cells, on agarose/ethidium bromide gels by the procedure as described earlier (Manna et al., 2010). For the microscopic analyses, after treatment, cells were washed with PBS followed by fixation with paraformaldehyde and mounted with a coverslip using the mounting media with DAPI for control cells and without DAPI for NDs treated cells. Images were observed by confocal microscopy with an inverted laser scanning confocal microscope (Leica Microsystems, Germany).

3. Results and discussion

3.1. Observations from electron beam analysis (TEM/HRTEM)

The formation of the NDs was studied by using electron beam analysis (TEM/HRTEM) in order to know their microstructure and nanostructure. The electron beam analysis of a representative sample of S1, S2, and S3 revealed that the carbon nanoparticles are unagglomerated types (Fig. 2a) and distributed uniformly sized with a crystalline phase. The electron beam analysis of a representative sample of S1, S2, and S3 revealed that the carbon nanoparticles are unagglomerated types (Fig. 2a) and distributed uniformly sized with a crystalline phase. The electron beam analysis of a representative sample of S1, S2, and S3 revealed that the carbon nanoparticles are unagglomerated types (Fig. 2a) and distributed uniformly sized with a crystalline phase.

Fig. 1. Showing the study area map of using Google earth and Respirable Dust Sampler and High Volume Sampler for the collection of TSP and PM₁₀.
(S4) shows the interplane spacing of 0.218–0.321 nm (2.18–3.21 Å) (Fig. 3c and d), which revealed the presence of nanodiamond phases (Das and Saikia, 2017; Kumar et al., 2015). These results are found to be in good agreement with the diamond phases of a cubic structure having lattice planes (111) as reported elsewhere (Das and Saikia, 2017; Kumar et al., 2015). In case of PM10-derived S4 sample (Fig. 3d), the interplanar spacing of 0.321 nm indicates the presence of sp2 hybridized structure of carbon (i.e. graphite). It was reported that the removal of complete graphite layer cannot be possible by simple oxidation due to interfacing between the structures of sp2 and sp3 (Kumar et al., 2015; Ferrari and Robertson, 2000). The elemental mapping of carbon and oxygen are also shown in Fig. 3e and f, respectively. The FFT image also revealed that the particles are hexagonal with a crystalline structure (see inside Fig. 3a). The TEM/HRTEM images, elemental characterizations, and FFT measurements of the interplanar lattice plane revealed the presence of nanodiamond particles in the CAs-derived samples rather than other carbon particles (Das and Saikia, 2017; Kumar et al., 2015). In addition, the structural properties of the CAs-derived NDs are found to be similar as reported for the formation of nanodiamonds (Lueking et al., 2006; Das and Saikia, 2017; Lueking et al., 2007; Kumar et al., 2015; Sun et al., 2014).

To further confirmed the formations as well as to evaluate the fascinating properties of fabricated NDs in our study, another advanced level of characterizations such as XRD, Raman spectroscopy, FTIR, XPS, UV–visible spectroscopy, and FL spectroscopy analysis was also carried out.
Fig. 3. (a & b) HRTEM images of nanocrystal as highlighted by hexagon ([extracted from a representative sample of TSP (S1–S3)]), the planner lattice of crystal was observed to be in the range of 0.220–0.266 nm (2.20–2.24 Å); (c & d) HR TEM images of nanocrystal [(derived from PM10 (S4) sample], the interplanar lattice fingers was measured to be 0.218–0.321 nm (2.18–3.21 Å); (a–d) FFT pattern insets are also showing the hexagonal crystalline structure of the highlighted area; (e–f) showing the C and O-mapping of nanodiamond extracted from representative TSP (S1–S3) sample using energy dispersive spectroscopy.
3.2. Observation from XRD analysis

The X-ray diffraction (XRD) analysis of a representative sample of S1, S2, S3, and S4 is shown in Fig. 4a, b, confirming the crystallites of the products (S1 to S4) having a plane of the cubic structure. A broad peak observed at $2\theta = 21.3^\circ$ (d spacing value = 4.16 Å) indicates the presence of silica substrate and the second peak found at $2\theta = 26.3^\circ$ (d spacing value = 3.38 Å) belongs to the crystal plane of graphite (002). This peak value is also observed in the spectra of S4 sample (Fig. 4b). Zou et al. (2010) reported that the peak at 20°–30° corresponded to the plane (002) of crystal graphite. It was also reported that the broad peak at 26° attributed to the nanodiamonds surrounded by an amorphous carbon matrix with abundant oxygen-containing functional groups (Das and Saikia, 2017; Lueking et al., 2006, 2007; Sun et al., 2014). The other peaks observed at $2\theta = 43.22^\circ$ (d spacing value = 2.0 Å) and $2\theta = 75.1^\circ$ (d spacing value = 1.26 Å) corresponding to the (111) and (220) cubic planes of the diamond, which indicated that the structure of CAs-derived NDs crystal is cubic (Plotnikov et al., 2016). This analysis revealed that the formed NDs consists of both sp² and sp³ hybridized carbon structure.

3.3. Observation from Raman spectroscopy analysis

The Raman spectra show mainly three absorptions bands for CAs-derived NDs samples (Fig. 4c–f). The NDs obtained from TSP as well as PM10 samples is evident from the peak at 1320 cm$^{-1}$, which is due to the phonon confinement effect (Himics et al., 2014). The first Raman peak ranging from 1320 to 1350 cm$^{-1}$ indicating near the position of D-band for sp³ hybridized carbon (Kumar et al., 2015). Many studies reported that diamond particle exhibits mainly Raman scattering peak at 1333 cm$^{-1}$ (Das and Saikia, 2017; Lueking et al., 2006; Kumar et al., 2015). The second peak in the Raman spectra occurs between 1435 and 1475 cm$^{-1}$ specify the D-band corresponding to the sp³ hybridized structure of carbon (Osswald et al., 2009). The third peak observed at 1600 cm$^{-1}$ and 1620 cm$^{-1}$ referred to as G-band attributed to the sp²
structure of carbon. The Raman analysis revealed that the nanodiamond particles are dominantly present in all the CAs-derived samples (S1–S4) rather than that of graphite.

3.4. Observation from FTIR and XPS analysis

FTIR and XPS characterizations of the CAs-derived NDs was carried out in order to know the chemical composition and surface states. Figures 5a and 5b shows the FT-IR spectral analysis of the CAs-derived NDs. From the Fig. 5a (a representative sample of S1, S2, and S3) and Fig. 5b (S4 sample), the peak observed at 660–685 cm\(^{-1}\) is due to the absorption of C—H bonds at the sp\(^3\) hybridized carbon atom (Dolmatova et al., 2014). The peak observed at 806 cm\(^{-1}\) (Fig. 5a) is assigned to the NO\(_2\) group. In both the spectra, the absorption peak observed in the range of 1027–1068 cm\(^{-1}\) and 1385–1400 cm\(^{-1}\) is due to the stretching vibration of C—O and OH group (Wolcott et al., 2014) along with other oxygen-containing functional groups (Korobov et al., 2013), respectively. The absorption band is found within the range of 1630 cm\(^{-1}\) corresponding to the bending vibration of hydroxyl (O–H) and carbonyl (C=O) group (Jiang et al., 1996; Jiang and Xu, 1995). Fig. 5a and b show the absorption band in the range of 2853–2854 cm\(^{-1}\) and 2926–2930 cm\(^{-1}\) attributed to the asymmetric and symmetric stretching vibrations of CH\(_3\) and CH\(_2\), respectively (Jiang et al., 1996). The broad peak observed at 3412–3434 cm\(^{-1}\) is due to the presence of hydroxyl (O–H) bonds. In the present study, the absorption bands observed for the hydroxyl groups are found to be more predominant over the carbonyl groups.

From the FTIR and XPS study (as discussed below) of CAs-derived NDs, it is observed that the fabricated NDs is highly functionalized with oxygen-containing hydrophilic functional groups, which leads to the highly soluble in water, as shown in Fig. 5c(i). The high solubility of the fabricated NDs in the water system is advantageous for their applications.

X-ray photoelectron spectroscopy (XPS) technique was used to determine the fraction of atoms (sp\(^2\) and sp\(^3\)) and chemical composition present in the nanodiamonds produced. In the XPS survey spectra as depicted in Fig. 6a and b, two major sharp peaks observed at 285 eV and 531 eV attributed to the presence of elements C and O, respectively. Fig. 6c and d show the high-resolution deconvolution XPS spectra of C1s of CAs-derived NDs obtained from representative samples of S1, S2, S3 and S4 sample, respectively. In Fig. 6c, two major peaks observed at 283.3 eV and 287.6 eV correspond to the sp\(^3\) hybridized and C=O, respectively (Shenderova et al., 2011). In Fig. 6d, two major peaks observed at 284 eV and 285.7 eV attributed to the sp\(^2\) hybridized carbon (Lesiak et al., 2009) and the presence of sp\(^3\) hybridized carbon (Bratt and Barron, 2014), respectively. Similarly, high-resolution deconvolution XPS spectra of O1s of CAs-derived NDs are depicted in Fig. 6e and f. The peak observed at 531 eV (Fig. 6e), 531.6 eV (Fig. 6f) correspond to the organic C=O. The XPS spectral data of the produced NDs in our present study also found to be comparable with the reported literature (Lim et al., 2016; Fujimoto et al., 2016). The authors mentioned that the presence of peak centered at 287.5 eV and 531.2 eV of binding energy indicates the carboxyl functional group on the surface of nanodiamond with high density (Lim et al., 2016; Fujimoto et al., 2016).

![Fig. 5.](image-url) (a and b) FTIR analysis of nanodiamond [(derived from representative TSP (S1-S3) and PM\(_{10}\) (S4) sample)]; (c) (i) image of nanodiamond extract which are irradiated in day-light time; (ii) image of nanodiamond extract which are radiated or excited under UV light at 365 nm showing blue fluorescence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
3.5. Observations from UV–visible and fluorescence spectroscopy (FL)

The photo-physical properties of the CAs-derived NDs (S1, S2, S3, and S4) were investigated by using ultraviolet (UV–Vis) spectroscopy and FL spectroscopy. Fig. 7a shows the UV–visible spectroscopic analysis of the NDs samples obtained from TSP and PM10 samples, which indicated the presence of nanodiamonds-like structure with a similar shape in the range of 200–800 nm as reported elsewhere (Lueking et al., 2006; Das and Saikia, 2017; Lueking et al., 2007; Kumar et al., 2015; Sun et al., 2014). However, no clear peaks are detected in the range of visible region, while very sharp peaks are observed in the range of 200–210 nm. The absorption peak observed at 210 nm (5.9 eV) is due to the π-π* and π-π* transition of C–C and C–O bonds present in the NDs samples, respectively (Yang et al., 2018).

Fig. 6. (a and b) XPS survey spectra of nanodiamond (proportionate representative sample derived from TSP (S1–S3) and PM10 (S4); (c and d) deconvoluted XPS C1s spectra of nanodiamond [(proportionate representative sample derived from TSP (S1–S3) and PM10 (S4)]; (e and f) deconvoluted XPS O1s spectra of nanodiamond [(proportionate representative sample derived from TSP (S1–S3) and PM10 (S4)].
This peak attributed to the intrinsic absorption of nanodiamond that is larger than a diamond of 5.5 eV because of minor size-induced blue shift (Xiao et al., 2015).

The CAs-derived NDs samples are found to be blue-fluorescence under UV-light (at 365 nm) with considerable intensity as depicted in Fig. 5c(ii), which is one of the fascinating property of nanodiamonds (Das and Saikia, 2017).

Fig. 7b–c shows the FL spectra of produced NDs samples under the excitation wavelength of 300 nm. The maximum FL intensity was observed at 430 nm, corresponding to the blue regions. One representative sample was prepared by proportionate mixing of NDs samples (S1, S2, S3) obtained from the three TSP samples only to see the fluorescence property at the different excitation wavelength (280-340 nm, at an increment of 20 nm). The FL properties of the representative NDs sample is observed to be excitation dependent as depicted in Fig. 7d and comparable with the other reported studies (Baker and Baker, 2010; Shen et al., 2012). With the increase of excitation wavelength, the FL spectra of NDs sample is observed to be shifted from red to green and yellow regions which signify as a major characteristic of nanodiamond. This phenomenon is occurred due to the presence of numerous fluorophore or chromophore system (aromatic and oxidation groups) in NDs, that is also confirmed from the FT-IR and XPS data as discussed above.

### 3.6. Observation from Zeta potential analysis

Zeta potential is the net charge or electrostatic potential at the plane of particle-sliping (Gibson et al., 2007). Zeta potential analysis was carried out to know the stability and surface charge of the CAs-derived NDs. The Zeta potentials of the NDs were found to be in the range of $-24$ mV to $-25$ mV (see Fig. 8a and b), which indicated that produced NDs suspensions are stable (Gibson et al., 2007). The negative Zeta potential values were observed due to the presence of oxygen-containing functional groups, such as carbonyl (C=O) and carboxyl (COOH) groups which are dissociated in the surface of diamond particles (Ginés et al., 2017).

### 3.7. Toxicological characteristics of NDs

The cytotoxicity and genotoxicity analysis was performed to evaluate the toxicity levels of CAs-derived NDs for their further utilization. The normal kidney epithelial (NKE) cells were treated with NDs at the dose of 5, 10, 20, 50, 100, 150, and 200 $\mu$g/mL for 24 h. The results demonstrated that NDs did not cause any change in the cell viability compared to those seen in the control group.

Confocal microscopic studies also demonstrated no significant changes in cell morphology upon exposure of different compounds at a dose of 200 $\mu$g/mL for 24 h compared to Fig. 7.
the control cells. The cell line treated by the CAs-derived NDs demonstrated blue-fluorescence properties, indicating the positions of NDs (Fig. 11). So the toxicity study confirmed that the CAs-derived NDs are non-toxic and the cell viability at high rates make them a biocompatible for different biological application such as bioimaging or fluorescence imaging.

4. Conclusions

The carbonaceous atmospheric aerosols (TSP and PM10) was investigated for the fabrication of NDs. After our extensive experimentation and analysis, we summarize that both TSP and PM10 could be utilized for the fabrication of NDs by using the ultrasonic-assisted oxidative chemical technique. The crystalline structure and nominal size of the carbon nanoparticles (4–17 nm) obtained from electron beam study (TEM/HRTEM) along with other characterizations signify the fabrication of NDs rather than the other carbon nano-materials. The optical properties of the produced NDs are found to be excitation dependent with maximum FL intensity at 430 nm, attributing to the blue regions. A stable blue-fluorescence was observed under UV-light (at 365 nm). The produced NDs are also found to be non-toxic and bio-compatible, which indicates its suitability for the bioimaging application. This study opens a new avenue for alternative use of carbonaceous aerosols for the fabrication of non-toxic NDs, leading to a reduction of atmospheric PMs pollution. However, further extensive study is needed to make a golden standard method to fabricate NDs from different aerosol sources.

Acknowledgments

Authors express thanks to Director (CSIR-NEIST) for his permission to publish the paper. The NCAP-COALESCE project (GPP-325) funded by the Ministry of Environment, Forest and Climate Change, New Delhi and FTT project (MLP-1006) funded by CSIR, New Delhi are duly acknowledged by the authors. Authors are thankful to the esteemed reviewers for their constructive comments to improve the revision.
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