PAPER

Multifunctionalities enabled by the synergistic effects of mesoporous carbon dots and ZnO nanorods

T Kavitha and S Kumar

1 James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom
2 Department of Mechanical Engineering, Khalifa University of Science and Technology, Masdar Campus, Masdar City, PO Box 54224, Abu Dhabi, United Arab Emirates

E-mail: s.kumar@eng.oxon.org

Keywords: carbon dot, nanohybrid, multifunctional material, photocatalytic, antibacterial, supercapacitor, light energy harvesting

Abstract

In this study, CD/ZnO nanohybrids were synthesised by a simple, one-pot, cost-effective method and their structure and properties were investigated by physicochemical methods. The CD/ZnO nanohybrid exhibits excellent sunlight induced photocatalytic and antibacterial activity validating the development of remarkably efficient catalytic systems and effective bactericidal agents. The IV measurements of CD/ZnO nanohybrid shows over 12-fold increase in photocurrent compared to ZnO, opening pathways for the fabrication of efficient light harvesting system. Electrochemical property measurements demonstrate that CD/ZnO nanohybrid has large integral area of cyclic voltammetry loop, demonstrating their potential for supercapacitor applications. The study presents green chemistry strategy for the synthesis of CD/ZnO nanohybrids which exhibit multifunctionalities due to the synergy between CD and ZnO. The findings of the study demonstrate the potential of CD/ZnO nanohybrids for a multitude of energy and environmental solutions.

Introduction

Modern society faces humongous challenges both in terms of rapidly growing energy demand and environmental protection, due to declining reserve of environmentally unfriendly fossil fuels, increasing population and global warming [1]. Development of new sustainable technologies has become indispensable [2]. To ameliorate the problem of energy crisis and pollution, the scientific community have focussed on creating new functional nanomaterials and technologies. In particular, state-of-art in hybridizing nanomaterials has been demonstrated to be a dexterous and dynamic strategy as it leads to synergistic effects that couple the finest advantages of associated ingredients and accord with new unusual attributes in addition to their intrinsic properties [3]. In the realm of newly developed functional materials, nanocomposites comprising carbon nanostructures and metal oxide nanoparticles emerged as excellent candidates for the fabrication of novel class of devices for emerging applications from high energy depository and conversion, solar cells, environmental remediation, catalysis, sensors to electronic devices [4–16].

Carbon dot (CD) is a zero-dimensional, relatively new associate of carbon family with closely arranged carbon atoms and alluring photo luminescent properties [17, 18]. CDs have been explored extensively considering their virtues such as ease of synthesis from any abundantly available carbon rich matrix, strong photoluminescence, chemical stability, superior water solubility, strong chemical inertness, ease of chemical functionalization, biocompatibility, little photobleaching, and low cost [19]. Based on the fluorescence and biocompatible properties, applications such as photocatalysts, organic photovoltaics, bio-imaging, and biosensors have been explored. Recently CDs have been employed in applications such as solar cells, LEDs, photodetectors and sensors due to their homogenous shape, tuneable surface chemistry, and extremely small size with high specific surface area, and optical and electronic properties [20]. CDs are also thought-out as recent environmentally safe material for electrodes [21] to enhance the ionic motion, electron transport, and increase the junction area amid electrode and electrolyte in supercapacitors [22, 23]. Besides aforementioned properties,
mesoporous surface will make CD an outstanding member due to high surface area, abundant pore volumes, controllable pore sizes and shapes and other nano-attributes for a multitude of sustainable applications [24].

Zinc oxide (ZnO) has been an assuring n-type semiconductor due to its wide bandgap (approximately 3.37 eV), large exciton binding energy (approximately 60 meV), long term stability, good electrical and optical properties, low-cost, non-toxicity, and ease of preparation. It has been explored for a variety of applications such as photocatalyst, LEDs, photovoltaic units, UV detectors, gas, chemical and biosensors [25–28]. However, the large bandgap of ZnO limits its application in light harvesting. Owing to photocorrosion and rate of recombination of photo-induced electron hole pairs, their real time application as a photocatalyst is still challenging both technologically and fundamentally. These limitations could be resolved by bandgap engineering and enhancing the optical properties of ZnO to visible spectrum [29]. ZnO could be promising for supercapacitors owing to their large surface area and pseudo-capacitance through Faraday redox reaction but it suffers during the charge/discharge step from low rate capability and reversibility during the charge/discharge procedure [30].

Hybrid hetero-nanostructures formed by combining mesoporous CD and photo luminescent ZnO could be the best strategy to overcome the limitations of individual components and bestow the hybrid with improved properties [31]. For instance, doping of mesoporous CD with ZnO could alter the band gap because of transfer of charge from CD to ZnO and thus augments the charge separation, enabling photocatalytic and photovoltaic applications [32]. With respect to supercapacitors, double-layer capacitance of mesoporous CD and pseudo capacitance of ZnO could enhance the total capacitive performance [21, 23]. To the best of authors’ knowledge, this is perhaps the first study on hybridizing mesoporous CD with ZnO nanorods to assess their potential for a multitude of applications such as visible light photocatalysts, solar cells, supercapacitors and antibacterial materials.

In this study, we demonstrate a simple route for the synthesis of CD/ZnO nanohybrid complying with green chemistry principle (see figure 1). The as-prepared CD/ZnO nanohybrid manifests CD with mesoporous morphology and spherical shape of diameter \( \sim 50 \text{ nm} \) and rod shaped ZnO with a diameter of around 50 nm and length of 200–250 nm. The optical attributes were studied by UV–vis and PL spectra. A methodological investigation of photocatalytic and antibacterial activity towards degeneration of methyl orange dye and E. coli bacteria, respectively was carried out in the presence of CD, ZnO and CD/ZnO nanohybrid under visible light and the nanohybrid exhibits the excellent results. The IV characteristics and electrochemical properties were also studied to assess the potential of CD/ZnO nanohybrid for energy applications.

**Experimental methods**

**Chemicals**
The date palm fronds (DPFs) harvested from Masdar City landscapes in Abu Dhabi, UAE were dried in open atmosphere to obtain dry matter (total solid content of approximately 92%). DPFs were compressed into particles of size less than 2 mm using IKA Werke MF 10.1 mill and stored in zipper bags. Zinc nitrate hexahydrate was purchased from Sigma Aldrich and used as such. Deionized water with resistivity 15 M\( \Omega \)-m was used for the entire analysis.

**Synthesis of CD, ZnO and CD/ZnO nanohybrids**
The CDs were synthesized by pyrolysis (300 °C) of DPFs following our previous report [24]. The ZnO is made by simple thermal decomposition of Zinc nitrate hexahydrate at 350 °C for 3 h and used as obtained. The CD/ZnO nanohybrids were prepared by the addition of 1 g of ZnO into 10 ml aqueous solution containing CD (0.2 g).
followed by stirring at 350 rpm for 2 h. The resultant solution was then centrifuged at 9500 rpm to remove any unreacted CD and dried.

Characterization of CD, ZnO and CD/ZnO nanohybrids
The structural study of CD and ZnO were conducted using a Quanta 250 ESEM, UK by coating with Au of 10 nm thickness. A transmission electron microscopy (TEM) study for CD and CD/ZnO nanohybrids was done in Tecnai TF20, 200 kV instrument. The XRD experiments of CD/ZnO nanohybrids were performed on XRD PANalytical Empyrean. The UV–vis and photoluminescence (PL) spectrum studies were conducted on a UV/Vis spectrophotometer thermo scientific genies 10 S and LS–55 fluorescence spectrometer, respectively. The semiconductor behavior of ZnO and CD/ZnO nanohybrid were investigated by two–probe method using probe station (CASCADE, USA). Electrochemical properties were measured using a conventional three-electrode experimental cell equipped with a standard calomel reference electrode, working electrode, and a platinum foil counter electrode. All electrochemical measurements were carried out with 0.10 M Na2SO4 as electrolyte and the cyclic voltammetry (CV) curves were recorded on electrochemical work station (CHI600, CH Instruments, USA).

Photocatalytic experiments
To demonstrate the visible light photocatalytic activity of CD, ZnO and CD/ZnO, 0.1 mg of methyl orange (MO) model dye was supplemented into 10 ml water with 0.1 mg of CD, ZnO and CD/ZnO nanohybrid, respectively and stirred in the dark for 30 min to attain equilibrium and irradiated with sunlight. Jasco V–650 UV–visible spectrophotometer was used to measure the concentration of MO from 2 ml of sample taken out every 60 min.

Antibacterial experiments
Antibacterial activities of CD, ZnO and CD/ZnO nanohybrids were evaluated against E. coli by optical density measurements. In the 96 well plate, 170 μl of bacterial suspension was dropped into 30 μl CD, ZnO and CD/ZnO nanohybrids (50 μg ml −1), respectively and exposed to 50 W LED light. The optical density measurement was used to assess the viability of cells and the structure of bacteria after 6 h treatment with CD/ZnO nanohybrids.

Results and discussion
The synthesis of CD/ZnO nanohybrids involves mixing and sonication of CD and ZnO nanorods, centrifugation, washing and drying. The attachment of mesoporous CD onto ZnO nanorods matrix is achieved through non–covalent intermolecular interactions such as charge - transfer interactions and van der Waals forces [33]. These interactions at the interface of CD and ZnO could play a vital role in bestowing the CD/ZnO nanohybrids with synergistic properties.

Figure 2(a) shows the SEM image of ZnO nanostructures exhibiting rod like morphology. The ZnO nanorods are nearly uniform with a typical diameter of around 50 nm and length of 200–250 nm. Their structure appeared to be defect–free. TEM image of CD reveals (figure 2(a)) spherical morphology with uniform size, mesoporous surface, excellent dispersion and an average diameter of 35 nm. The monodisperse nature of CD with hydrodynamic diameter of 1575 nm was confirmed from dynamic light scattering study. In TEM images of CD/ZnO nanohybrids, the apparent contrast between CD and ZnO nanorods demonstrate strong evidence for the formation of CD/ZnO nanohybrids. The intimate contact of CD on ZnO illustrates the interactions between them and is expected to improve the properties of CD/ZnO nanohybrids.

The XRD pattern of the CD/ZnO nanohybrid is presented in figure 3. It manifests peaks of ZnO nanorods at 2Θ = 28.4°, 31.6°, 36.3, 47.7°, 56.6°, 62.8°, 66.3°, 68.1°, 69.1°, 75.6°, 77.2° which could be accredited to (100), (002), (101), (102), (110), (103), (200), (112), (201), (004) and (202) crystalline planes of hexagonal ZnO wurtzite structure (ICPDS No. 396-1451), respectively. The peak at (101) plane describes that the preferred orientation of ZnO nanorods is along (101) crystalline plane. The peak at 2Θ = 25.5° could be accounted for (002) graphitic plane from amorphous CD [25]. The results confirmed the presence of amorphous CD and crystalline ZnO in CD/ZnO with no apparent impact on the purity and crystallinity of the nanohybrids.

Figure 4 epitomizes the absorption and emission spectra of CD, ZnO and CD/ZnO nanohybrid in water. In figure 4(a), the UV–vis spectrum of CD in water shows a clear band of absorption at 203 nm which could be accredited to the π–π* changeover of the aromatic sp2 hybridized carbon core of mesoporous CD (bandgap = 5.01 eV) [34] whereas ZnO nanorods have absorption at 373 nm [35]. The absorption spectrum of CD/ZnO nanohybrid shows the absorption band of both CD and ZnO, while the ZnO has an absorption cut-off edge at 396 nm, featuring a red shift. This shift could be ascribed to the interaction of mesoporous CD on ZnO...
nanorods and thus extending the absorption edge to visible regime from UV. The doping of ZnO with mesoporous CD which comprises only C, would have established an intermediate energy level just above the valence band of ZnO and decreased the band gap [36]. At room temperature, PL of mesoporous CD (figure 4(b)), photo excited at 205 nm, revealing a predominant emission peak at 475 nm due to bandgap transitional changes in the conjugated π-domains. The PL spectra of pure ZnO excited at 396 nm emits around 500 nm which is generally accredited to stoichiometry related defects, zinc vacancies, along with interstitial zinc

Figure 2. (a) FESEM image of ZnO nanorods, and TEM images of (b) CD, (c) and (d) CD/ZnO nanohybrids.

Figure 3. XRD pattern of CD/ZnO nanohybrids.
and structural defects [37]. PL spectra of CD/ZnO nanohybrids show photoluminescence at 525 nm when excited at 475 nm with red shift and increased intensity. The luminescence with increased intensity could be due to the maximum interfacial contact between CD and ZnO nanorods, which plays a part in the establishment of the surface defects and thus contributing to intense photoluminescence [38]. The red shift supports the electron transfer from ZnO nanorods to CD [39]. Hence, figure 4 illustrates electron and energy transfer from ZnO to CD due to the interfacial contact, playing an influential part in exemplifying the properties of the CD/ZnO nanohybrids.

The visible light catalysed degradation of MO dye by CD, ZnO and CD/ZnO nanohybrid is illustrated in figure 5(a). It shows that over 90% of MO was decomposed by CD/ZnO nanohybrid within an hour and hence featuring an excellent photocatalytic activity compared to its individual constituents. The improved photocatalytic activity could be due to better dispersion of CD onto ZnO nanorods, improving photo absorption limit in the visible spectrum of light. The photocatalyst reusability is one of the assets of heterogeneous catalyst and therefore we assessed the stability of photocatalyst over 5 cycles as shown in figure 5(b). There is no significant decrease in photocatalytic activity and hence CD/ZnO could serve as stable and reusable visible light photocatalyst.

The detailed mechanism for improved visible light catalytic activity of CD/ZnO nanohybrid could be derived as follows: first the mesoporous CDs adsorb the dye molecules due to its high adsorption capacity, then with irradiation, photo-induced electron transfer occurs from ZnO to CD while hole stopovers structurally and electronically near ZnO which can efficaciously impede the electron-hole pair recombination and reduce interfacial transfer time and thus photodegrade the organic dye adsorbed onto CD [5]. Shortly, the exemplary
sunlight driven photocatalytic activity of CD/ZnO nanohybrid is perhaps, due to attributes such as high adsorption capacity of CD, charge separation and efficient interfacial charge transfer. Figure 6(a) illustrates the development curves of E. coli under visible light in medium loaded with CD, ZnO, and CD/ZnO nanohybrid at different time intervals. The control experiment with no nanoparticle showed highest bacterial growth, indicating that visible light radiation alone could not control bacterial growth. Under visible light radiation, CD/ZnO nanohybrid has exemplary antibacterial activity compared to CD and ZnO. Thus, the line of antibacterial activity against E. coli under visible radiation is CD < ZnO < CD/ZnO. As shown in figure 6(b), the morphology of E. coli treated with CD/ZnO for 6 h under visible light demonstrates that the cell wall was corrugated and break open resulting in endoplasmic spill over with serious alteration in structure of bacterial cell emanating cell death. The phenomenal photo-enhanced antimicrobial activity of CD/ZnO nanohybrid is perhaps on the grounds of synergy between CD and ZnO and reactive oxygen species production through effective interfacial charge transfer from ZnO to CD. The detailed mechanism of cell death by CD/ZnO nanohybrids could be explained as follows: Absorption of light results in electron-hole pair production due to excitation from ZnO to CD, where photo excited electrons present in the conduction band reduces dissolved oxygen in the system to superoxide radicals, whereas the hole loaded at valence band combines with water physically captivated on the oxide surface and produces hydroxyl radicals, hydrogen peroxide, and/or protonated superoxide radical. These ROS thus authoritatively result in cell death through cell wall rupture and endoplasmic spill over [40].

The I-V characteristics of ZnO and CD/ZnO nanohybrids under illumination were studied to augment and envisage the intricate photocatalytic degradation mechanism of nanohybrid as presented in figure 7. Compared to ZnO, the CD/ZnO nanohybrid demonstrates ~12 times increased photocurrent due to the synergy between CD and ZnO in the nanohybrid. This proves that upon visible light irradiation, photo-induced electron transfer takes place from ZnO to CD while hole halts electronically and structurally near ZnO. This could efficaciously impede the electron-hole pair recombination and reduce interfacial transfer time, bestowing the best photocatalytic efficiency [41]. Additionally a 12 fold increase in photocurrent could open up promising strategy for designing light harvesting system based on sustainable CD/ZnO nanohybrids [42].

To explore the synergistic effects of CD and ZnO, we studied electrochemical performances of CD, ZnO and CD/ZnO nanohybrid. Figure 8(a) shows box shaped CV curve of CD signifying excellent charge propagation at the surface of electrode [23], whereas ZnO nanorod (figure 8(a)) shows anamorphic CV response owing to internal resistance of the electrode and pseudo capacitance [43]. Figure 8(b) shows that the CV curve of CD/ZnO nanohybrid is neither box type nor anamorphic but has the largest integral area within the loop justifying the positive synergistic effects of CD and ZnO.. The CV curve of CD/ZnO nanohybrid is the resultant of synergism of electrical double layer capacitance and pseudo capacitance due to the reaction between ZnO and electrolyte, i.e., the intercalation and deintercalation of Na⁺ from electrolyte into ZnO. In addition, the large surface area could have increased the sufficient liquid-solid interfacial area and the unique structure of CD/ZnO nanohybrid could have facilitated the rapid transfer of electrons amidst the active materials and charge collector leading to enhanced supercapacitance of the nanohybrid [30]. These results evidence the good electrochemical behaviour of CD/ZnO nanohybrids which make them potential electrode material for supercapacitors.
Conclusions

We have successfully synthesized CD/ZnO nanohybrid via a simple, one-pot, cost-effective method adhering to green chemistry principles. The morphology, crystallinity, and optical physicochemical attributes of CD/ZnO nanohybrid were studied by appropriate analytical techniques. The potential of the CD/ZnO nanohybrid as photocatalyst was demonstrated by photocatalytic decomposition of an organic pollutant, methyl orange, under sunlight. They also exhibited exemplary photocatalytic antibacterial activity under visible light irradiation. The enhanced light driven catalytic activity was due to the production of more free radicals through increased separation efficiency. The CD/ZnO nanohybrid manifests a ~12-fold increase in photocurrent compared to ZnO nanorods. Furthermore, it exhibited superior electrochemical behaviour. The multifunctionalities of CD/ZnO nanohybrid were due to the synergy between CD and ZnO and we believe this multifunctional, non-toxic, metal free, highly efficient CD/ZnO nanohybrid could be a promising candidate as photocatalyst, visible light bacteriocide, light harvesting system and supercapacitor.

Acknowledgments

The authors would like to acknowledge the financial support from the Abu Dhabi National Oil Company (ADNOC) under award no: EX2016-000010. Authors would like acknowledge Johannes Schneider for his help in the preparation of figures.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

S Kumar @ https://orcid.org/0000-0002-3386-8012

References

[1] Kumar P S et al 2014 Hierarchical electrospun nanofibers for energy harvesting, production and environmental remediation Energy Environ. Sci. 7 3192–222
[2] Sun J-K and Xu Q 2014 Functional materials derived from open framework templates/precursors: synthesis and applications Energy Environ. Sci. 7 2071–100
[3] Li X and Zhi L 2018 Graphene hybridization for energy storage applications Chem. Soc. Rev. 47 3189–216
[4] Li W, Liu J and Zhao D 2016 Mesoporous materials for energy conversion and storage devices Nature Reviews Materials 1 16023
[5] Bozetine H et al 2016 Green chemistry approach for the synthesis of ZnO–carbon dots nanocomposites with good photocatalytic properties under visible light J. Colloid Interface Sci. 465 286–94
[6] Liu X et al 2017 Noble metal–metal oxide nanohybrids with tailored nanostructures for efficient solar energy conversion, photocatalysis and environmental remediation Energy Environ. Sci. 10 402–34
[7] Gupta T K, Choosri M, Varadarajan K M and Kumar S 2018 Self-sensing and mechanical performance of CNT/GNP/UHMWPE biocompatible nanocomposites J. Mater. Sci. 53 7393–52
[8] Reddy S K, Kumar S, Varadarajan K M, Marpu P R, Gupta T K and Choosri M 2018 Strain and damage-sensing performance of biocompatible smart CNT/UHMWPE nanocomposites Mater. Sci. Eng. C 92 957–68
[9] Arif M F, Kumar S, Gupta T K and Varadarajan K M 2018 Strong linear–piezoresistive-response of carbon nanostructures reinforced hyperelastic polymer nanocomposites Composites Part A: Applied Science and Manufacturing 113 141–9
[10] Patole S P, Reddy S K, Schiller A, Askar K, Prusty B G and Kumar S 2019 Piezoresistive and mechanical characteristics of graphene foam Nanocomposites ACS Appl. Nano Mater. 2 1402–11
[11] Patole S P, Arif M F and Kumar S 2018 Polyvinyl alcohol incorporated buckypaper composites for improved multifunctional performance Compos. Sci. Technol. 168 429–36
[12] Patole S P, Arif M F, Susantyoko R A, Almeirhi S and Kumar S 2018 A wet-filtration-zipping approach for fabricating highly electroconductive and auxetic graphene/carbon nanotube hybrid buckypaper Sci. Rep. 8 12188
[13] Kumar S, Gupta T K and Varadarajan K M 2019 Strong, stretchable and ultrasensitive MWCNT/TPU nanocomposites for piezoresistive strain sensing Composites Part B: Engineering 177 107285
[14] Mora A, Verma P and Kumar S 2020 Electrical conductivity of CNT/polymer composites: 3D printing, measurements and modeling Composites Part B: Engineering 183 107600
[15] Arif M F, Alhashmi H, Varadarajan K M, Koo J H, Hart A J and Kumar S 2020 Multifunctional performance of carbon nanotubes and graphene nanoplatelets reinforced PEEK composites enabled via FFF additive manufacturing Composites Part B: Engineering 184 107625
[16] Kanagaraj A B et al 2018 Mechanical, thermal and electrical properties of LiFePO4/MWCNTs composite electrodes Mater. Lett. 230 57–60
[17] Bhunia S K, Saha A, Maity A R, Ray S C and Jana N R 2013 Carbon Nanoparticle-based fluorescent bioimaging probes Sci. Rep. 3 1473
[18] Baker S N and Baker G A 2010 Luminous carbon Nanodots: emergent nanolights Angew. Chem. Int. Ed. 49 6726–44
[19] Melling T T, Cywiński P J and Baldwin J 2016 White carbon: fluorescent carbon nanoparticles with tunable quantum yield in a reproducible green synthesis Sci. Rep. 6 28537
[20] Genc R et al 2017 High-capacitance hybrid supercapacitor based on multi-colored fluorescent carbon-dots Sci. Rep. 7 11222
[21] Liang Y, Zhang W, Wu D, Ni Q-Q and Zhang M Q 2018 Interface engineering of carbon-based nanocomposites for advanced electrochemical energy storage Adv. Mater. Interfaces 5 1800430
[22] Xu J et al 2016 Carbon quantum dots/nickel oxide (CQDs/NiO) nanorods with high capacitance for supercapacitors RSC Adv. 6 5541–6
[23] Umnikrishnan B, Wu C-W, Chen J W P, Chang H T, Lin C H and Huang C-C 2016 Carbon dot-mediated synthesis of manganese oxide decorated graphene nanosheets for supercapacitor application ACS Sustainable Chemistry & Engineering 4 3008–16
[24] Kavitha T and Kumar S 2018 Turning date palm fronds into biocompatible fluorescent mesoporous carbon dots Sci. Rep. 8 16269
[25] Kavitha T, Gopalan A I, Lee K-P and Park S-Y 2012 Glucose sensing, photocatalytic and antibacterial properties of graphene–ZnO nanoparticle hybrids Carbon 50 2994–3000
[26] Yadav A B, Parvathi P V L and Thabassum S 2019 Effect of precursor chemistry on the structural and sensing properties of hydrothermally grown nanorods Appl. Phys. A 125 446
[27] Sannakshappanavar B S, Yadav A B, Byrareddy C R and Murty N V L N 2019 Fabrication and characterization of Schottky diode on ultra thin ZnO film and its application for UV detection Mater. Res. Express 6 116445
[28] Yadav A B, Parvathi P V L and Thabassum Shaik R 2019 Zero bias UV detection and precursor effect on properties of ZnO nanorods grown by hydrothermal method on SiO2/p-Si substrate Thin Solid Films 685 343–52
[29] Yu H et al 2012 ZnO/ carbon quantum dots nanocomposites: one-step fabrication and superior photocatalytic ability for toxic gas degradation under visible light at room temperature New J. Chem. 36 1031–5
[30] Zeng H et al 2013 Synthesis, optical and electrochemical properties of ZnO nanowires/graphene oxide heterostructures Nanoscale Res. Lett. 8 133
[31] Chang H and Wu H 2013 Graphene-based nanocomposites: preparation, functionalization, and energy and environmental applications Energy Environ. Sci. 6 3483–507
[32] Mathur A, Dutta S B, Pal D, Singh J, Singh A and Chattopadhyay S 2016 High efficiency epoxiazil-graphene/silicon-carbide photocatalyst with tunable photocatalytic activity and bandgap narrowing Adv. Mater. Interfaces 3 1600413
[33] Dhotel A, Chen Z, Delbreilh L, Youssef B, Saiter J-M and Tan L 2013 Molecular motions in functional self-assembled nanostructures *Int. J. Mol. Sci.* **14** 2303–33
[34] Wang C, Xu Z, Cheng H, Lin H, Humphrey M G and Zhang C 2015 A hydrothermal route to water-stable luminescent carbon dots as nanosensors for pH and temperature *Carbon* **82** 87–95
[35] Schneider J J et al 2008 A printed and flexible field-effect transistor device with nanoscale zinc oxide as active semiconductor material *Adv. Mater.* **20** 3583–7
[36] Chang Q-Q, Cui Y-W, Zhang H-H, Chang F, Zhu B-H and Yu S-Y 2019 C-doped ZnO decorated with Au nanoparticles constructed from the metal–organic framework ZIF-8 for photodegradation of organic dyes *RSC Adv.* **9** 12689–95
[37] Taunk P B, Das R, Bisen D P and Tamrakar R K 2015 Structural characterization and photoluminescence properties of zinc oxide nanoparticles synthesized by chemical route method *Journal of Radiation Research and Applied Sciences* **8** 433–8
[38] Suzuki K et al 2015 Energy transfer induced by carbon quantum dots in porous zinc oxide nanocomposite films. *The J. Phys. Chem. C* **119** 2837–43
[39] Liu J, Bi H, Cesar Morais P, Zhang X, Zhang F and Hu L 2017 Room-temperature magnetism in carbon dots and enhanced ferromagnetism in carbon dots-polyaniline nanocomposite *Sci. Rep.* **7** 2165
[40] Liu J et al 2018 Photo-enhanced antibacterial activity of ZnO/graphene quantum dot nanocomposites *Nanoscale* **10** 158–66
[41] Mandal S K et al 2019 Engineering of ZnO/rGO nanocomposite photocatalyst towards rapid degradation of toxic dyes *Mater. Chem. Phys.* **223** 456–65
[42] Barman M K, Mitra P, Bera R, Das S, Pramanik A and Parta A 2017 An efficient charge separation and photocurrent generation in the carbon dot–zinc oxide nanoparticle composite *Nanoscale* **9** 6791–9
[43] Li Z, Zhou Z, Yun G, Shi K, Lv X and Yang B 2013 High-performance solid-state supercapacitors based on graphene-ZnO hybrid nanocomposites. *Nanoscale Res. Lett.* **8** 473