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Mini-Review on Graphene Quantum Dots as an electro-catalyst in fuel cell

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ABSTRACT

Due to a significant increase in the demand for usable power, research focused on energy-material relations has garnered considerable attention. Fuel cells, characterized by their high efficiency, high energy density, quiet operation, and environmental friendliness, are regarded as a promising future power source that provides clean power at the point of use. The incorporation of functionalized graphene quantum dots (GQDs) has been shown to enhance catalytic activity and stability, making them attractive materials for various device applications, particularly in fuel cells. This review presents an overview of different synthesis methods for GQDs and discusses the utilization of GQD-doped composites with optimized content and enhanced electro conductivity as electrocatalysts in fuel cells.

Keywords: Fuel cell, Graphene Quantum Dot, Electro catalyst, conductivity

1. Introduction

In the past decades, research on new environmentally friendly energy sources and their practical applications has drawn a growing amount of interest due to technological advancement, the rapid expansion of energy consumption in people's lives, and the depletion of fossil fuel supply [1-3]. Among the proposed clean energy sources, an innovative technology based on the utilization of fuel cells (FCs) has been demonstrated to be a crucial conduit for converting processes to electricity generation and thus for tackling energy and environmental issues. In addition, they are small, discreet, and have much lower EIs than other conventional devices or technologies during their operational phase [4]. FCs have additional benefits. For instance, they can be used for applications ranging from a few watts to several gigawatts [5]. A fuel cell is a device that produces electricity by chemical reactions at its two electrodes, a positive electrode (a cathode) where a reduction reaction (or gain of electrons) happens, and a negative electrode (an anode) where electrons are lost (or oxidation reaction) [6].

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Thus, electrons move from the negative terminal to the positive one, generating an electric current that flows from the Cathode to the Anode of the fuel cell. This is a Reaction of Oxidation and Reduction (ORR) [7]. Additionally, it has an electrolyte solution or a selectively permeable membrane that allows only suitable ions to travel between the cathode and anode chambers. FCs are superior to conventional technologies due to their unique properties, which include energy savings, great thermodynamic efficiency, and power generation. [8-14]. The classification of fuel cells is based on the utilization of electrolytes and fuel, as shown in **Table 1**. [15, 16]. Despite the fact that FCs are considered to be more environmentally friendly than conventional energy conversion systems, there are still noticeable operational and environmental drawbacks between FC varieties. The life cycle assessment (LCA) of FCs is similar to that of conventional power sources, owing to the environmental impact statement (EIs) associated with fuel sourcing and material acquisition, whether for precious metals used in low-temperature FCs or thermally and chemically stable materials used in medium- and high-temperature FCs [17].

The slow oxygen reduction reaction (ORR) on the cathode side of fuel cells is the present barrier in the

technology behind fuel cells. The development of novel electro catalysts for fuel cells, one of the most recent energy resources, in order to reduce the needed overvoltage is an essential feature in the electrocatalysis sector. To date, the chosen electrocatalysts are Pt and platinum group metals (PGM), which pose a substantial obstacle to the commercialization of fuel cells due to their scarcity and high cost. The discovery of low-cost alternative catalysts with excellent activity and endurance in the ORR, including metal-free heteroatom doped carbon materials, has received considerable attention, [18-20] such as zero-dimensional graphene quantum dots (GQDs) have attracted great interest also are expected to be one of the most promising alternatives to Pt-based catalysts due to their low-cost, high electro catalytic activity, selectivity, and stability [20-25].

2. Synthesis of GQD

Most of the synthesis techniques for graphene quantum dots (GQDs) can be categorized into two main approaches: top-down and bottom-up methods. In the top-down strategy, GQDs are derived from larger carbon-based materials such as graphene, fullerenes, and carbon nanotubes by means of physical or chemical cutting processes. On the other hand, the bottom-up approach involves controlled chemical reactions using molecular precursors to gradually build GQDs [26].

2.1. Top – Down approaches

2.1.1. Hydro and solvo-thermal methods

For the preparation of graphene quantum dots (GQDs), hydrothermal and solvothermal approaches are commonly employed as simple and rapid methods. These methods involve the cutting of carbon materials into GQDs under high temperature and high-pressure conditions. Prior to the reactions, the carbon compounds typically undergo intense oxidation treatments [28, 29].

Pan et al. were the first to attempt the synthesis of GQDs with sizes ranging from 5 to 13 nm using oxidized graphene sheets as the raw material through the hydrothermal technique at 200°C [30]. It was reported that the oxidized graphene sheets (GSs) contained oxygen-enriched functional groups such as ketone, carboxyl, hydroxyl, and ether groups, which enhanced the quantum yield. Through hydrothermal de-oxidation, the oxygen atoms from the epoxy groups were removed, resulting in the formation of GQDs with an average diameter of 9.6 nm.

The size of GQDs can be easily controlled using the solvothermal technique with various organic solvents, including dimethyl sulfoxide (DMSO), dimethylformamide (DMF), or benzene. The final size and morphology of the resulting GQDs can be directly influenced by the physicochemical properties of the solvent. For example, sonicating graphene oxide (GO) in DMF solvent can produce green-emitting fluorescent GQDs by breaking down the graphene oxide [31]. The photoluminescence characteristics of the GQDs can be adjusted by combining methanol and methylene chloride as the solvents and using water as the mobile phase during an 8-hour process [32].

2.1.2. Ultrasound Techniques

Ultrasonic is a simpler approach to shearing the carbon layer materials into GQDs by low and high creation of alternating pressure waves in liquid [26]. In a typical technique, the sonication of the mixture has occurred to form GQDs for 12h after GSs oxidation in a high concentration of sulfuric or nitric acids [24]. By this typical approach, a 3-5 nm diameter size of GQDs monodisperse was created. In a recent study, a straightforward ultrasonic technique with chemical activation utilizing KOH for GQDs synthesis was described by sonicating few-layer graphene sheets and activated graphene directly [27]. After numerous purifications, GQDs were synthesized as 3-5 nm average diameter with bluish fluorescence.

2.1.3. Lithography Process

Large graphene flakes obtained through microchemical cleavage of graphite crystals were employed using the

Table 1. Fuel cell types and their features

Type	Temperature °C	Fuel	Electrolyte Mobile	Ion
PEM: polymer electrolyte membrane	70–110	H_2 CH_3OH	Sulfonated polymers (Nafion®)	$(H_2O)_nH^+$
AFC: alkali fuel cell	100–250	H_2	Aqueous KOH	OH^-
PAFC: phosphoric acid fuel cell	150–250	H_2	H_3PO_4	H^+
MCFC: molten carbonate fuel cell	500–700	Hydrocarbons CO	$(Na,K)_2CO_3$	CO_3^{2-}
SOFC: solid oxide fuel cell	700–1000	Hydrocarbons CO	$(Zr,Y)O_2\text{-}\delta$	O^{2-}

standard "scotch-tape" exfoliation process in a top-down manner [37]. These graphene flakes were then transferred onto a SiO2/silicon wafer with a thickness of 300 nm. Electron-beam lithography was utilized to fabricate graphene quantum dots (GQDs) from the graphene flakes. Several research groups have successfully achieved the generation of 30-50 nm GQDs using this method [38]. It is important to note that there is a minimum size limitation imposed by the resolution of the lithography device.

However, isolating and characterizing graphene flakes can present challenges. Firstly, optical microscopy is employed to identify single-layer graphene flakes, and secondly, Raman spectroscopy is the primary method for analyzing such flakes. The quality of the obtained GQDs is significantly influenced by various factors, including the thickness of the SiO2 layer, surface cleanliness, and the procedures involved in dividing the graphite chemical bonds [39].

2.1.4. Exfoliation by "Nanotomy" Technique

Mohanty et al. report that graphite dissection is the first step of a two-phase fragmentation procedure [28]. Following a diamond-induced "nanotomy" procedure, the graphite bonds were chemically exfoliated using super acids. The graphene nanostructures that were produced displayed geometries of nano squares, nano triangles, and nanorectangles with diameters ranging from 10 to 50 nanometers and having smooth edges and zig-zag patterns. The use of a high-speed self-regulating nanotoning system makes it possible to generate GQDs on a wide scale; nevertheless, the sizes of the GQDs produced by this method are larger than those acquired from chemically and electrochemically produced ones.

2.1.5. Chemical Exfoliation

In this method, artificial graphite was synthesized through the thermal treatment of hexa-peri-hexabenzocoronene at 1200°C. The resulting graphite was then subjected to exfoliation using the Hummers method [41]. The obtained graphene oxide was subsequently refluxed with poly (ethylene glycol) (Mw 1500) for two days, followed by reduction with hydrazine. The resulting graphene quantum dots (GQDs) exhibited a disk-like shape with a diameter of 60 nm and an average thickness of 2-3 nm, which is equivalent to three to four layers of graphene.

Recently, this method has been further improved by introducing a single-step, wet-chemical procedure for GQDs preparation [42]. This modified approach also led to the production of micro-sized carbon fibers with a reinforced surface. The carbon fibers were treated at different temperatures for 24 hours in concentrated

H_2SO_4 and HNO_3, resulting in GQDs with adjustable diameters: 1-4 nm at 80°C, 4-8 nm at 100°C, and 7-11 nm at 120°C. Moreover, this method has been successfully employed using CX-72 carbon black as the starting material to synthesize GQDs with sizes ranging from 15 to 18 nm [43].

2.1.6. Microwave-Assisted Exfoliation

Microwave methods have gained popularity in the production of nanomaterials due to their numerous advantages, including rapid and high-yield synthesis of both organic and inorganic compounds [44]. Li et al. conducted a study on the synthesis of green-yellow luminescent graphene quantum dots (GQDs) using microwave-assisted chemical reduction. In this method, graphene oxide (GO) nanosheets were treated with strong acids (HNO_3 and H_2SO_4) for a duration of 3 hours [24]. Subsequently, the GO nanosheets underwent further reduction using $NaBH_4$, resulting in a transformation of the luminescence from green-yellow to blue. Notably, despite the change in luminescence color and an increase in intensity, the size and shape of the GQDs remained unchanged.

2.1.7. Graphene Sheet Scissoring Using an Electrochemical Technique

This method was considered a reliable strategy for making fluorescent C-points [29, 30], regarded as a potential technique for the manufacturing of GQDs. Here, a huge graphene layer that was electrochemically cleaved was treated with oxygen plasma to increase its water solubility [31]. The graphene sheets (GSs) were produced by oxidizing reduced graphene oxide (rGO) with $KMnO_4$ and reducing it with aqueous N_2H_4 [32]. Then, they were subjected to a 3 V potential, which caused electrolyte ions to permeate the graphene layers and induce the oxidation of C-C bonds inside the graphene structure. For cyclic voltammetry, an external voltage (swept between 0.3 and 0.3 V) was supplied to a graphene film (working electrode) immersed in 0.1 M phosphate buffer solution (PBS). The resultant GQDs were collected using a membrane bag after filtering and dialysis. This technique yields monodisperse GQDs with a narrow size range (between 3-5 nm in diameter and 1-2 nm in thickness) (about three layers of graphene). Electrochemical oxidation causes sheet fragmentation into GQDs at the faults induced by GSs' chemical and physical treatment.

2.2. Bottom-Up Approaches

2.2.1. Pyrolysis of Precursors

Pyrolysis is the process of breaking down organic molecules into their component parts at very high

temperatures. This process takes place in the absence of oxygen and creates irreversible chemical and physical compositional changes. By changing the carbonization conditions and spreading the pyrolyzed products in alkaline media, pyrolysis of a precursor such as citric acid can produce GQDs with a diameter of 15 nm (0.5–2.0 nm) [33]. Prolonged heating of the precursor can cause complete carbonization, resulting in GO nanostructures just 100 nm in width (1 nm thickness). Tang et al. pyrolyzed glucose using a combination of hydrothermal and microwave techniques (595 W for 5 minutes) to produce GQDs with a diameter ranging from 2.9 to 3.9 nm [34]. By varying the microwave reaction period (1–9 minutes), the size of GQDs may be adjusted between 1.65 and 21 nanometers. The ratio of carbon, hydrogen, and oxygen content was generally 1:2:1 for the carbohydrate precursors; however, hydrogen and oxygen predominated in the form of carbonyl, hydroxyl, and carboxyl groups since these functional groups often dehydrate through a hydrothermal process.

2.2.2. Step-by-Step Organic Synthesis

Due to the rigid backbones of polycyclic aromatic hydrocarbon (PAH) molecules, high-quality, homogeneous, and well-ordered GQDs can be produced by incorporating PAHs into this method. However, due to their aggregated state caused by insufficient lateral aliphatic side-chains and the edges of aromatic molecules interacting, the creation of large GQDs with acceptable solvability is extremely challenging [35-37]. Covalent bonding decorates the edges of graphene moieties with 2,4,6-triakyl phenyl groups and reduces the surface contacts between graphene layers [38]. This leads to the formation of three-dimensional cages around the graphene moieties, which increases the distance between each layer and improves the solubility of bigger GQDs that contain the following conjugated carbon atoms: 168 (C168, 2), 132 (C132, 1), and 170. (C170, 3). Recently, electron-removal or electron-donating groups have been applied to the surface of GQDs to modulate their redox potential and bandgap [37]. This method has the ability to synthesize a range of functional GQDs and exemplifies the typical benefit of wet-chemistry approaches in the synthesis of well-ordered graphene nanostructures. However, it remains difficult to synthesize, purify, and characterize bigger GQDs using these techniques [39].

2.2.3. Decomposition of Fullerene

As a carbon supply, fullerene C60 was employed to construct homogeneous GQDs on a Ru (0001) substrate [40]. The latter catalyzed the disassembly of the C60 cage, and the resulting fragments were then reconstituted into clusters. When C60 samples were washed at 500–550 K, thermal hopping and dissociation initiated by adatom-vacancy processes were seen on the terrace using scanning tunneling microscopy. At 650 K, the C60 molecules fully disintegrated into carbon clusters. Clusters generated from C60, with a diffusion coefficient of 10^{-15}–10^{-16} cm^2 s^{-1}, consist of a sequence of atomically uniform GQDs, which are difficult to get when derived from other predecessors, such as C_2H_4. When C60 was annealed for 2 minutes at 725 K, various GQD forms began to develop (e.g., triangular, parallelogram-shaped, and trapezoid-shaped). A further increase in annealing temperature to 825 K for 2 minutes resulted in the formation of hexagonal GQDs of 5-10 nm in size.

In addition, Chen et al. found that KOH oxidizes and activates graphene-oxide-like quantum dots (GOLQDs) [41]. A modified version of the Hummers process was used to synthesize GOLQD on a wide scale, with a yield of about 25% wt. from oxidizing C60 molecules. The GOLQDs were very water-soluble and contained carbon rings in addition to the hexagonal structures. After drying, the average height of the substrates was around 1.2 nm, and the diameter distribution ranged from 0.6 to 2.2 nm [42].

3. GQD as an Electro-Catalyst Material

Nanoparticles have evolved into stable heterogeneous catalysts and substrate frameworks with a great deal of surface area, which enhance compounds for a longer duration than conventional materials. In addition, the activity of Nano catalysts can be tailored by modifying their size, shape, composition, and surface morphology. Carbon, graphite, graphene, inorganic nanotubes, carbon nanotubes, aluminum, silver, cobalt, copper, zinc oxide, silicon dioxide, iron oxide, cerium oxide, titanium dioxide, quantum dots, and clays have demonstrated promising results in previous studies involving various catalytic reactions, making them a potential candidate for industrial applications in the scientific community [43, 44]. GQDS as a catalyst have a variety of applications, such as electrocatalysts.

GQDs have various disadvantages, such as being difficult to assemble into a film and having low conductivity, etc. It may be possible to overcome some of the obstacles and improve their overall performance by forming GQD composites or doping them with other materials. This might then lead to the development of a wide variety of innovative applications. Polymer materials [45, 46] and nano-materials [47-52] may be combined with GQDs to create composites. More active sites meant a faster charge transfer rate in the GQD/PPy composite film because of the film's porosity features.

Future potential for composites of GQDs and organic materials is without question immense. It is interesting to note that Zor et al.[53] developed a brand-new multifunctional composite made up of magnetic silica beads, GQD, and molecularly imprinted polypyrrole. The optical and magnetic characteristics of the composite were improved. As a result of its improved qualities, the GQD composite might be used in a wide variety of contexts. In recent years, there has been an increasing interest in producing innovative GQD composites. The nanofiber combination of GQDs and polyaniline was created by the lab of Mondal's [54] for use as a supercapacitor electrode material. The composite material increased the 1 Ag-1 current density and cycle stability. Chen et al.[55] assembled 0D GQDs and 3D graphene (3DG) using a novel, non-toxic electrochemical technique. The high surface area and active sites of the GQDs-3DG composite material were employed to develop a supercapacitor with improved performance. External quantum efficiency (EQE) of 57681% (at -1 V bias) at wavelength 340 nm was demonstrated by Dhar and colleagues [56] for a combination of ZnO and GQDs, which they showed can improve the performance of UV photodetectors. The performance of the composite material consisting of ZnO nanorods/poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and GQDs was significantly superior to that of GQD-modified ZnO nanorods and pure ZnO nanorods. Other ZnO shapes, such as leaf-shaped ZnO (L-ZnO) [57], were also employed to produce composites with GQDs. In the same manner, nanocomposites composed of TiO_2 and GQDs were produced by Bu [58] . Due to the increased energy barrier between NGQDs and B-TiO_2, the nanocomposites utilized as photocatalysts demonstrated extraordinarily high photocatalytic activity, resulting in enhanced light absorption and higher electron density. Ji et al. [59] constructed a lithium-ion battery by combining MnV12 with GQDs in a composite material. The performance of the lithium-ion battery can be optimized by using bar-shaped composites, which can enhance the interfacial contact area, improve charging and discharging behavior, and therefore optimize the battery's overall performance. Another interesting experiment [60] was conducted by assembling Mn_3O_4 and GQDs into nanocomposites. These nanocomposites can vary the energy level of the materials without the need for doping with heteroatoms or regulating the size and shape of GQDs. In many catalytic applications, composite materials containing GQDs are preferred because of their high surface area to volume ratio. Catalyst composites of GQDs and Au nanoparticles were synthesized by Wu et al.[61]. A wide variety of inorganic materials, such as SnO_2[62], ZnS [63], MoS2 [64], ferroelectric liquid crystal [65], ceria [66], Zn [67], and Fe_2O_3 [68] have been employed to create composites with GQDs. Copper GQD composites exhibit superior electrocatalytic activity compared to platinum-GQD due to the increased oxygen affinity of copper [69]. In fuel cells, the replacement of N atoms with GQDs has the potential to modify the electronic structure and provide an increase in the number of active sites for the oxygen reduction reaction (ORR) [70-72]. N-doped GQDs (N-GQDs) with oxygen-rich functionalities have been synthesized by Qu et al., and these N-GQDs have been shown to have enhanced electrocatalytic reactivity toward ORR [73]. Another paper demonstrated the effect of N-GQD size on ORR, revealing that increasing NGQD size results in an increase in current density [74]. N-GQDs were electrochemically produced, and their size-dependent ORR electrocatalytic activity was assessed [75]. N-GQD-based hybrid electrocatalysts have also been created recently to take advantage of the promising features of N-GQDs for ORR [72, 76]. Particularly, the integration of N-GQDs on various carbon supports has garnered considerable interest for the fabrication of alternative, highly efficient electro catalysts for oxygen reduction reaction (ORR) [72, 77]. Materials made of heteroatom-doped nanocarbon, such as carbon nanotubes, graphene, and porous carbon, display excellent stability and electro catalytic performance for the oxygen reduction reaction (ORR) [78, 79]. Hydrothermally attached boron- and nitrogen-doped GQDs on graphene platelets have been shown to be an effective electrocatalyst for oxygen reduction reaction (ORR) [76]. Boron-nitrogen-doped GQDs have the maximum activity for performing ORR in contrast to other materials as a result of the synergistic effect that boron and nitrogen have on one another [80].

Similarly, a novel class of GQD-coated graphene nanoribbons with enhanced electro catalytic activity in alkaline media was created using a one-step reduction procedure [23]. The electro catalytic activity for the oxygen reduction reaction was studied by Fan et al., who found that the presence of multiple types of N-C or C-S-C bonding in metal-free N,S-GQDs considerably increased this activity (ORR) [81].

Using a simple self-assembly technique, N-GQDs/graphene nanocomposites have been synthesized and employed as an effective electro catalyst for oxygen reduction reaction (ORR) [82]. NGQDs-graphene demonstrated exceptional electro catalytic activity and long-term stability. Two-dimensional (2D) metal chalcogenides, particularly molybdenum disulfide (MoS_2), have been shown to be prospective candidates

for ORR because to their unique features, such as strong electrical conductivity and vast surface area [83, 84]. N-GQDs hybrid played a good role in ORR, especially that made by using pyridine as a nitrogen precursor. N-GQDs have their uses in electro-catalytic activity [85].

In brief, GQD composites and N,S-GQDs are endowed with unique structural features and are promising candidates for metal-free electrocatalysts and improve the performances of devices. Novel functionalities of GQDs can be developed using composites and doping, which would open up new applications for GQDs.

4. Future prospects

Among the suggested clean energy sources, an innovative technology based on the use of microbial fuel cells (MFCs) has been proved as a critical pathway for bioconversion processes towards electricity generation, then for addressing energy and environmental problems. Three special features, including energy saving, less sludge production, and less energy production, make MFCs outstanding compared with the existing technologies [8-14]. Among these cells, the proton exchange membrane fuel cell (PEMFC) is one of the most promising technologies for transportation. The most significant part of MFCs is the proton exchange membrane (also termed the polymer electrolyte membrane (PEM)) with high protonic conductivity, low electronic conductivity, Fuel gas or liquid impermeability, Good mechanical strength in both dry and hydrated conditions, and High oxidative and hydrolytic stability in the environment of fuel cells, responsible for the proton transfer from the anode to the cathode and therefore the complete fuel cell's performance. The PEMFC, which is composed of a perfluorinated polymer membrane, Nafion, exhibits high proton conductivity at a certain range of temperature and humidity, but they still have some barriers, such as high fuel permeability and high cost [11-14]. However, developments of cost-effective materials and advanced membranes have been successful for reducing this limitation [86].

Studies have been focused on alternative solutions, including the fabrication of nanocomposite membranes by incorporating different nanofillers [87-89]. Zero-dimensional (0D) materials such as silica nanoparticles [90-92], ceramic oxides nanoparticles [93, 94], etc [89, 95, 96] and one-dimensional (1D) nanomaterials such as carbon nanotube [97, 98], titania [99, 100], titanate [101] nanotube have been incorporated into the polymer matrix as versatile nanofillers. These nanocomposite membranes exhibited great enhancement in performance, endowing strong competitiveness in fuel cell application. 2D single-layer nanostructure called graphene with sp2-hybridized conjugated carbons [102, 103] can be investigated due to the exotic electrical, mechanical, and thermal properties [103-105] as well as its high surface area, chemical stability, and low fabrication costs [106, 107]. Zarrin et al. fabricated a nanocomposite membrane filled with functionalized graphene oxide (GO), and both proton conductivity and single-cell performance were significantly enhanced [108].

High proton conductivity, low water permeability, and good thermal and mechanical stability are some properties of the recent developed fuel cell materials and membranes [109].

The conversion of 2D graphene into 0D graphene quantum dots (GQDs) can be targeted by many studies in future years. The newly synthesized membrane can show greater thermal stability due to the formation of three-dimensional network structures in the presence of Functionalized Quantum Dots (FQDs) [110].

4. Conclusions

Recent advancements in sustainable and renewable energy sources have led to the emergence of fuel cells as a promising technology. Graphene quantum dots (GQDs), as innovative nanostructured materials, can be synthesized using diverse methods, resulting in active units with adjustable electronic and optical properties. These GQDs show great potential in a wide range of energy and environmental applications. Fuel cells offer numerous possibilities for electricity generation, but they are subject to limitations associated with the cost of catalysts and electrodes. Therefore, subsequent developments have focused on the exploration of new materials, hybrids, and composites aimed at addressing the limitations of conventional fuel cell components.

Nomenclature

GQDs	Graphene quantum dots
FC	Fuel cell
ORR	Oxygen reduction reaction
PEM	Polymer electrolyte membrane
AFC	Alkali fuel cell
PAFC	Phosphoric acid fuel cell
MCFC	Molten carbonate fuel cell
SOFC	Solid oxide fuel cell
PGM	Platinum group metals
GSs	Graphene sheets
DMSO	Dimethyl sulfoxide
DMF	Dimethylformamide
KOH	Potassium hydroxide
rGO	reduced Graphene oxide
PBS	Phosphate buffer solution
PAH	Polycyclic aromatic hydrocarbon
GOLQDs	Graphene-oxide-like quantum dots

PPy	Polypyrrole
3DG	3D graphene
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate
L-ZnO	Leaf-shaped ZnO
B-TiO$_2$	Titanium dioxide (B)
2D	Two-dimensional
MFCs	Microbial fuel cells
PEMMFCs	Proton exchange membrane microbial fuel cells
0D	Zero-dimensional
1D	One-dimensional
GO	Graphene oxide
FQDs	Functionalized Quantum Dots
LCA	life cycle assessment
EIs	Environmental impact statement

Acknowledgements

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