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Abstract

This review summarizes mainly the activity of our labs. We established more than one laboratory for materials synthesis, characterization, and applications. Our laboratories provide the synthesis of several nanoparticles including metal oxide nanoparticles (e.g., Fe_3O_4, ZnO, $ZrOSO_4$, MoO_{3-x}, CuO, $AgFeO_2$, Co_3O_4, SiO_2, and $CuFeO_2$), metallic nanoparticles (Ag, Au, Pd, and Pt), carbon-based nanomaterials (graphene, graphene oxide, reduced graphene oxide, and carbon dots (CDs)), biopolymers (cellulose, nanocellulose, TOCNF, alginate, and chitosan), organic polymers (conjugated polymers, covalent-organic frameworks (COFs), and intrinsic microporous polymers), and hybrid materials e.g. metal-organic frameworks (MOFs). These materials were applied for energy, environmental, and biomedicine applications. They were applied in several fields such as environmental-based technologies (e.g., water remediation, air purification, gas storage), energy (production of hydrogen, dimethyl ether, solar cells, and supercapacitors), and biomedical sectors (sensing/biosensing, cancer therapy, and drug delivery). They can act as efficient adsorbents and catalysts to remove emerging contaminants such as metals, dyes, drugs, antibiotics, pesticides, and oils in water via adsorption. They can be also used as catalysts for catalytic degradation, reduction, and oxidation of organic pollutants. They can be used as filters for air purification by removing greenhouse gases such as carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter (PMs). They can be used for hydrogen production via water splitting, alcohol oxidation, and hydrolysis of $NaBH_4$. Biomedical applications such as antibacterial, drug delivery, and biosensing were also involved.

Keywords: Materials; MOFs; Energy; Environmental; Biomedicine.

Introduction

Materials are objects containing a mixture of substances. They can be classified based on several strategies including 1) physical and chemical properties; 2) origin (e.g., natural or synthetic); and 3) biological function. Natural materials can be prepared using raw materials via several procedures including purification, extraction, and shaping. On the other side, synthetic materials can be prepared via several procedures. Human classified their prehistory based on material types into; Stone Age, Bronze Age, and Iron Age. The steel age, plastic age, and silicon age were named for the 19th century, the middle of the 20th century, and the second half of the 20th century, respectively. Materials advanced several applications including energy [1–4], environmental, analytical techniques [5–10], and biomedical applications [11–14].

We have established an advanced multifunctional materials laboratory (**Figure 1**). Our lab, an advanced multifunctional materials laboratory, can synthesize, characterize, and investigate applications for several fields. We can synthesize materials such as:-

1) Metal oxide nanoparticles, e.g., Fe_3O_4, ZnO, $ZrOSO_4$, MoO_{3-x}, CuO, CeO_2, $AgFeO_2$, Co_3O_4, SiO_2, and $CuFeO_2$.
2) Metallic nanoparticles, e.g., Ag, Au, Pd, and Pt.
3) Carbon-based nanomaterials, e.g., graphene, graphene oxide, reduced graphene oxide, and carbon dots (CDs).
4) Biopolymers e.g., cellulose, nanocellulose, TOCNF, alginate, and chitosan.
5) Organic polymers e.g., conjugated polymers, covalent-organic frameworks (COFs), and intrinsic microporous polymers.
6) Ionic liquids (Ils) [15–21].
7) Metallodrugs [22].

8) Hybrid materials e.g., metal-organic frameworks (MOFs).

We can do characterization using techniques such as X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), transmission electron microscopy (TEM), high-resolution TEM (HR-TEM), scanning electron microscopy (SEM), energy dispersive X-ray (EDX) analysis and mapping, atomic absorption flame spectroscopy (AAFS), UV-Vis spectroscopy, diffuse reflectance spectroscopy (DRS), and electrochemical measurements (cyclic voltammetry (CV), linear sweep voltammetry (LSV), electrochemical impedance spectroscopy (EIS), galvanostatic charge-discharge, differential pulse voltammetry (DPV), and Mott-Schottky (MS).

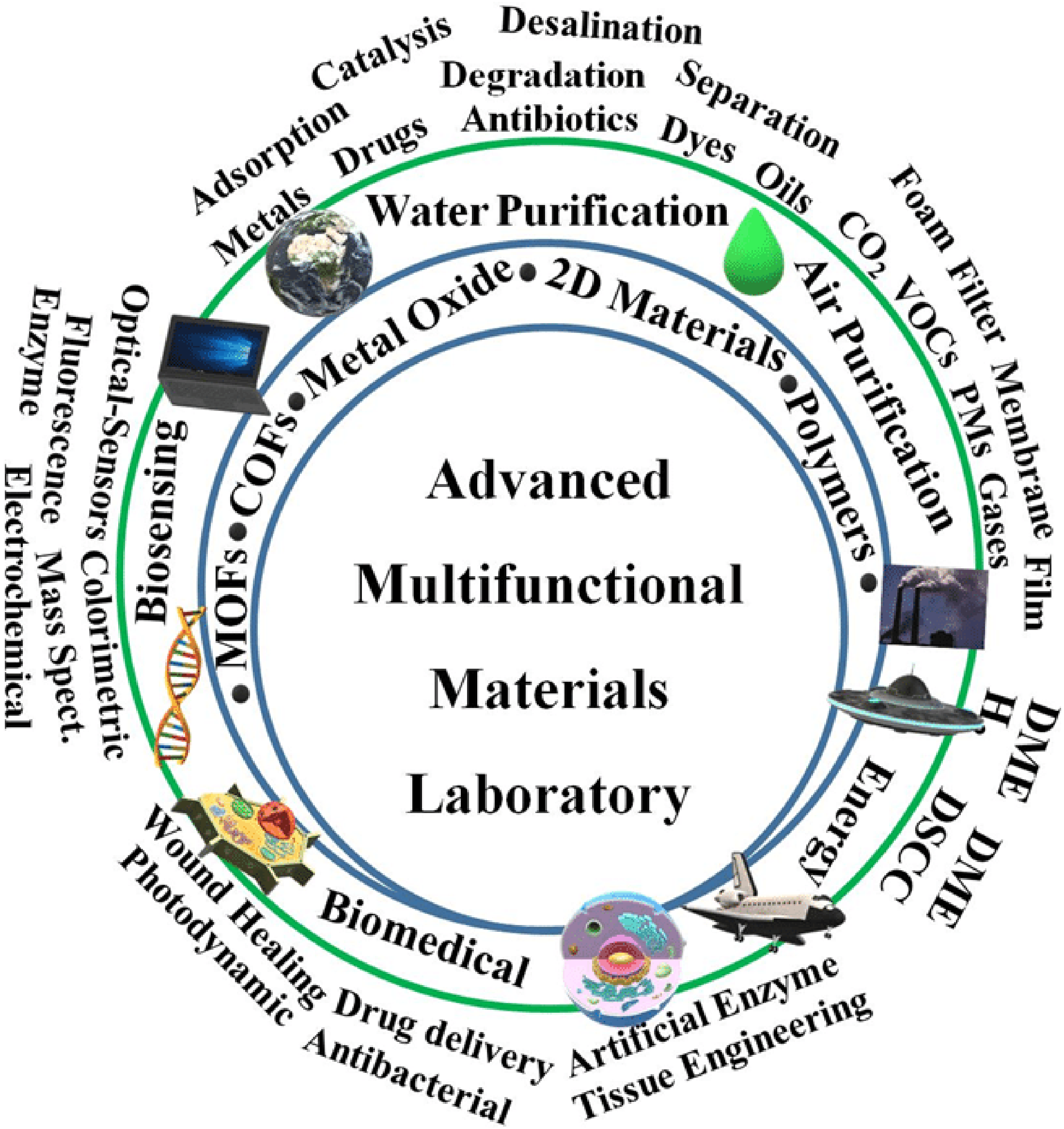

Figure 1 Advanced Multifunctional Materials Laboratory established by Dr. Hani Nasser Abdelhamid.

We can test any materials for several applications. Most of these applications are summarized as shown in **Figure 1**. We can report full analysis for applications such as:-

1. **Energy:-**

   a) Hydrogen generation via hydrolysis of sodium borohydride ($NaBH_4$).

   b) Photocatalytic water splitting for hydrogen generation.

   c) Photocatalytic alcohol oxidation for hydrogen generation and carbonyl compounds synthesis.

   d) Supercapacitors.

e) Lithium-ion Battery.

f) Dye-sensitizing solar cells (DSSCs) [23].

2. Environmental:-

a) Water treatment via pollutants removal e.g., adsorption and degradation.

b) Air purification; removal of greenhouse gases via adsorption.

c) Adsorption of volatile organic compounds (VOCs).

d) Photocatalytic degradation of drugs, antibiotics, and pharmaceuticals.

e) Heavy metal removal via adsorption.

f) Precious metal recovery.

3. Biomedical Applications:-

a) Cancer therapy; chemotherapy, photodynamic, and photothermal.

b) Drug delivery [24,25].

c) Gene delivery using cell-penetrating peptides (CPPs)[26,27].

d) Antimicrobial agents; antibacterial, and antifungal [28–33].

e) Nanotoxicity and Environmental fate for nanoparticles [34–36].

f) Bone regeneration.

g) Wound healing.

h) Tissue Engineering.

i) Nanozymes and MOFZyme (artificial enzyme based on MOFs materials)

j) Biosensing of biomarkers, biological heavy metals, enzymes, and proteins.

k) Detection and analysis of pathogenic bacteria.

l) Proteomics and clinical research [37].

m) Synthesis of biologically active compounds [38,39].

n) Investigate effective matrix for matrix-assisted laser desorption ionization mass spectrometry [40,41].

Metallic Nanoparticles

Metallic nanoparticles e.g., silver (Ag), gold (Au), palladium (Pd)[42], and platinum (Pt), advanced several applications. Silver nanoparticles have been used for many applications such as catalysis [43], energy [44], biosensing [45], laser desorption/ionization mass spectrometry (LDI-MS) and mass spectrometry imaging (MSI) [46], and others [47]. In our lab, we investigated Ag NPs' antimicrobial activity against bacterial flora of bull semen [48]. $AgFeO_2$ exhibit high antibacterial activity against several bacteria species [49,50]. Ag NPs were used as a probe for the detection of the freshness of fruits and vegetables via graphene-enhanced Raman spectroscopy (GERS) [51]. Silver nanoparticles can be used as a surface for microextraction proteins and other analytes for the analysis using surface-assisted laser desorption-ionization mass spectrometry (SALDI-MS) [52]. It can be also modified with chitosan for the separation and detection of biothiols [53].

The spermicidal effects of Ag NPs against flora bacteria were reported [48]. Silver salts were mixed with melamine. The mixture was then polymerized at 550 ^{o}C to generate graphitic carbon-embedded Ag NPs i.e. Ag@C NPs. Analytical techniques such as XRD, XPS, AAFS, TEM, and HR-TEM confirm the material's phases, composition, morphology, and particle size. Ag@C NPs display a particle size of 1-5 nm with an average particle size of 2.5 nm. The nanoparticles were embedded into carbon. Ag@C NPs were investigated as antimicrobial agents in bacteriospermia of fresh semen collected from five fertile bulls. They exhibited high antibacterial activity against bacteria species found in semen such as *Escherichia coli* (*E. Coli*), *Staphylococcus aureus* (*S. aureus*), and *Pseudomonas aeruginosa* (*P. aeruginosa*). It offered minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) of 3.125-12.5 μg/mL and 3.125 μg/mL, respectively. There was no detrimental effect ($P > 0.05$) on the percentage of sperm motility, plasma membrane integrity, acrosome integrity, and normal sperm morphology at concentrations of 15-30 μg/mL. Ag@C NPs is a promising antibiotic agent for bull semen extender during cold storage. It can be used in applications such as the field of artificial insemination [48]. The antibacterial activity of silver ferrite ($AgFeO_2$) was investigated. $AgFeO_2$ was modified with polyethylene glycols (PEGs) to render their dispersion high [49,50]. The antibacterial activity against pathogenic bacteria was quantified using plate counting, and the turbidity using optical density at wavelength 600 nm (OD_{600}). $AgFeO_2$ nanoparticles exhibited high antibacterial activity [49,50].

Silver nanoparticles were modified with 1-octadecanethiol (1-ODT)/4-aminothiophenol (4-AMP) and 1-ODT/1-thioglycerol (1-TG) to prepare Ag@ODT/AMP and Ag@ODT/TG, respectively [52]. The materials were used in microextraction as a pseudo-stationary phase via single-drop microextraction (SDME). They can extract proteins and peptides e.g., insulin, ubiquitin, t cytochrome c, cysteine, homocysteine, and lysozyme. The separated proteins can be detected after extraction using matrix-assisted laser desorption/ionization mass spectrometry (MALDI-MS). The method can be used for the analysis of real samples e.g., urine and milk [52]. Silver ferrite iron oxide nanoparticles ($AgFeO_2$ NPs) were reported for biothiols separation [53]. $AgFeO_2$ and $AgFeO_2$ modified chitosan ($AgFeO_2$@CTS NPs) can be used for the separation of biological thiols e.g., sulfamethizole, thiabendazole, dithiothreitol, and glutathione before the analysis using MALDI-MS and surface assisted laser desorption/ionization mass spectrometry (SALDI–MS) [53].

Au NPs enhanced GERS detection of the freshness of fruits and vegetables [51]. It can be used as a probe for surface-enhanced Raman spectroscopy (SERS, **Figure 2**). Au or Ag nanoparticles were synthesized into reduced graphene oxide nanosheets (e.g., Au@G and Ag@G). The materials can be used as a probe for the analysis of the freshness of fruits and vegetables (e.g., Carrot, Wax apple, Lemon, Red pepper, and Tomato) [51]. One-pot synthesis of Au NPs@carbon dots was reported for the cytosensing of metals in cancer cells [54]. Au NPs enhanced the analysis of simple molecules to intact cells using SALDI-MS [55].

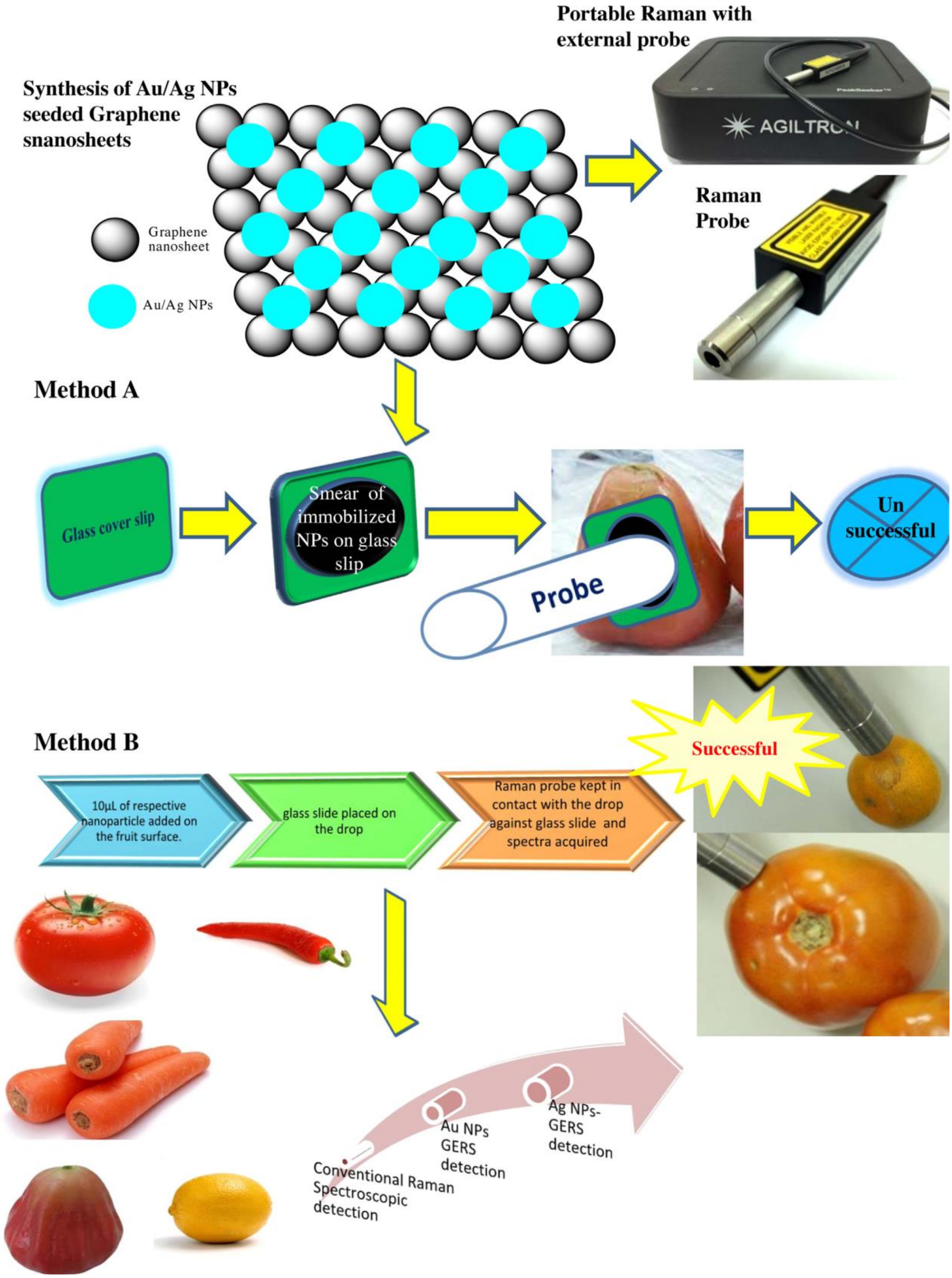

Figure 2 Schematic representation for GERS analysis of fruits and vegetables using Ag and Au NPs. Figure reprinted with permission from Ref. [51].

Carbon Nanomaterials and their Applications

Zero-dimension carbon can be also known as carbon dots (CDs), carbon nanodots (C NDs), or carbon quantum dots (CQDs) [56–62]. CDs were applied for several promising applications such as drug delivery [63], imaging [64–68], sensing [57,69–71], biosensing [78], energy-based applications [77], biomedical [72], and theranostic [73]. Carbon nanodots, including carbon dots and graphene quantum dots, carbon quantum dots (C QDs), or carbon dots (CDs), are emerging new carbon allotropes nanomaterials [74–76]. Carbon nanomaterials have advanced electrochemical-based applications [68,79]. CDs have advanced electrochemical applications [80,81] such as O_2 and H_2O_2 reduction [82], and biosensing of glucose [83–89].

C-dots can be doped with P [90], N [91], S [67], F [92], B [93], nitrogen and sulfur co-doped carbon dots (N, S-CDs) [94,95], and N/B [96]. C dots exhibit good optical properties including photoluminescence in the visible range [97,98], and high quantum yields (QY)[58,99]. The photoluminescence properties of CDs can be tuneable by changing their size, surface modification with functional groups at the graphitic edges of the materials, doping with heteroatoms, or selecting a suitable synthesis method [100,101]. They can be tuned offering fluorescence emission from blue to green [90,102]. It has been used for tackling COVID-19 [103], the virus [104]. It offered naked eye sensors [105]. N-doped CDs especially exhibit remarkable acid-evoked fluorescence enhancement under acidic conditions [106].

Two-dimensional carbon nanomaterials such as graphene, graphene oxide (GO), and reduced graphene oxide were intensively used for several applications. Graphene oxide was used for rare-earth metal adsorption [107]. It can be modified with thymine for selective detection of toxic heavy metals such as mercury (Hg(II)) [108]. The layer structure of GO enables the intercalation of an organic matrix such as sinapinic acid [109]. GO can be modified with SiO_2 for SALDM-MS [110]. It can use for heavy metal detection such as mercury ions [111], lipids

[112], and metallodrugs [113]. It exhibited high efficiency for bone and skin wound regeneration [114] and wound healing [115]. It can use for the drug delivery of in-soluble antibiotics such as gramicidin [116]. It can be used as a co-carrier to enhance the gene transfection of CPPs [117]. GO/cellulose nanocomposite accelerated skin wound healing [118]. Graphene can be used as a surface for SALDI-MS [119].

Metal Oxides

Metal oxides such as CeO_2 enabled the extraction and detection of pathogens proteins [120]. Fe_3O_4@ SiO_2 enabled rapid and direct identification of pathogenic bacteria from blood using [121]. Magnetic nanoparticles modified graphene oxide was reported for separation and preconcentration of pathogenic bacteria for sensitive detection using MALDI-MS [122]. Chitosan magnetic nanoparticles were reported for endotoxin separation and detection using SALDI-MS [123]. ZnO nanoparticle-modified polymethyl methacrylate was used for dispersive liquid–liquid microextraction for rapid analysis of pathogenic bacteria using MALDI-MS [124]. SnO_2@GO exhibited high antibacterial activity [125]

Commercial MoO_3 was used for the exfoliation to synthesize a few layers of MoO_{3-x} (**Figure 3**) [126]. The synthesis procedure involved the reflux of a bulk α-MoO_3 at 80 °C in water for 7 days. The prepared MoO_{3-x} nanosheets displayed infrared plasmonic properties offering localized surface plasmon resonance (LSPR) peaks at 954 and 1160 nm due to the oxygen vacancies upon light excitation. The plasmonic properties of the nanosheets can be enhanced using visible light irradiation for only 10 min. The materials were used as photocatalysts for dye degradation under visible light irradiation [126].

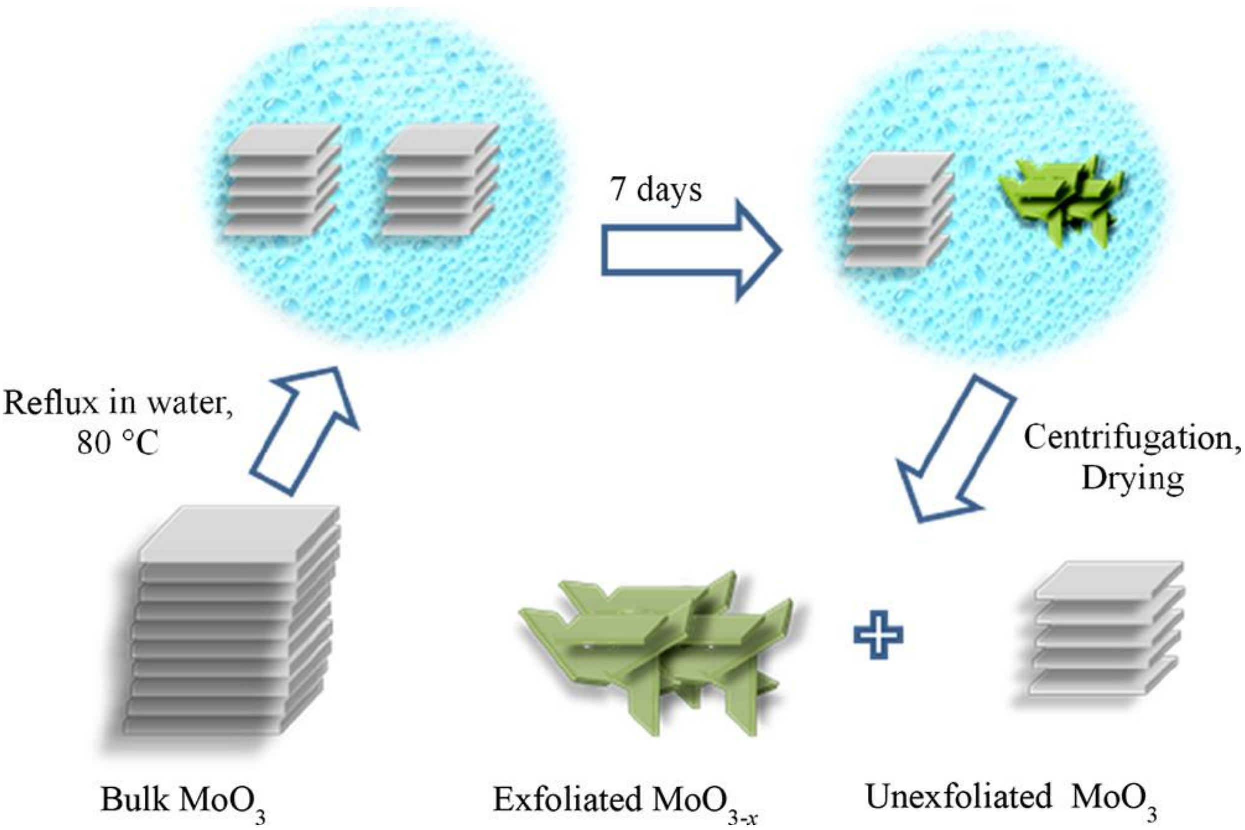

Figure 3 The Exfoliation of α-MoO_3 into MoO_{3-x} Nanosheets. Figure reprinted from Ref. [126]. This is an Open Access Article. Copyright belongs to the American Chemical Society (ACS).

Ruthenium oxide (RuO_2) with mesopore was synthesized via a surfactant-assisted procedure [127]. The materials exhibited higher catalytic oxidation activity of water using ceric ammonium nitrate (CAN).

Magnetic nanoparticles can be synthesized via several procedures including laser techniques [128]. Abdelhamid reviewed the application of delafossite nanoparticles in energy, nanomedicine, and environmental applications [129]. Magnetic nanoparticles of Fe_3O_4 were incorporated into polyplexes of CPPs/oligonucleotides (ONs) for cell transfection [130]. Three different oligonucleotides (e.g., plasmid (pGL3), splicing correcting oligonucleotides (SCO), and small interfering RNA (siRNA)) and six CPPs (e.g. PeptFect220 (denoted PF220), PF221, PF222, PF223, PF224, and PF14) were investigated. Magnetic nanoparticles enhanced the cell transfection up to 4-fold compared to the noncovalent PF14-SCO complex, which exhibited higher efficiency compared to a commercial vector called Lipofectamine™2000 [130].

Quantum Dots (QDs)

Quantum dots (QDs) are nanocrystals with particle sizes less than 10 nm [131]. Cadmium sulfide (CdS) quantum dots were used for selective biosensing of *Staphylococcus aureus* [132] and proteomics [133,134]. It can be used as a surface for SALDI-MS analysis of several analytes [135]. It enabled soft ionization offering the analysis of labile compounds such as metallodrugs [136]. It can also be used for fluorescence spectroscopy[137]. CdS QDs were in-situ grown into chitosan (CTS) enabling CdS QDs@CTS [138,139]. The material CdS@CTS exhibited selective interaction with Cu^{2+} due to the formation of $Cd_{1-x}Cu_xS$ [138,139]. The positive charge on chitosan exhibited also high interaction with the negative charge on the bacteria cell membranes [140]. CdS@CTS was also reported as a carrier for drug delivery of a natural anticancer drug called sesamol [141].

Biopolymers

Biopolymers including polysaccharides are intensively applied for biomedical applications [142,143]. Polysaccharides were applied as excipients for tablet formulation, dental implants, bone/tissue engineering, and drug delivery [142,143]. They can also be used for antimicrobial textiles [144–146]. Silver ferrite ($AgFeO_2$) can be modified with chitosan to render their external surface positive for biothiol separation [53]. Alginate can improve the gene delivery of oligonucleotides [147,148]. Modern technology such as 3D printing enabled simple processing of polylactic acid and hydroxyapatite for water treatment [149].

Cellulose-based advanced several applications such as biomedicine including antifouling [150–153]. They improved bioengineering [154] and water treatment via pollutants adsorption

[155]. Cellulose/ZIF-8 composite was used for water remediation via adsorption and catalytic degradation of organic pollutants such as dyes [156]. Cellulose enabled three-dimensional printing of porous materials such as leaf-like zeolitic imidazolate frameworks (ZIF-L), denoted as CelloZIF-L. Direct ink writing (DIW) or robocasting was used to proceed with the materials. The materials with a ZIF content of 84% were achieved. The materials were used for the adsorption of carbon dioxide (CO_2) and heavy metals offering capacities of 0.64-1.15 mmol/g (at 1 bar, 0 °C) and 554.8±15 mg/g, respectively. The adsorbent exhibited selectivity toward Fe^{3+}, Al^{3+}, Co^{2+}, Cu^{2+}, Na^{+}, and Ca^{2+} of 86.8%, 6.7%, 2.4%, 0.93%, 0.61%, and 0.19%, respectively [157]. Cellulose enabled also the processing of ZIF materials into filter paper [158,159] and foams [160]. Most of these biopolymers are biodegradable [161,162] compared to synthetic polymers [163]. They can proceed into the membrane for oil separation [161].

Chitosan improved gene delivery [164]. It can stabilize magnetic nanoparticles that enabled high-cell transfection [165]. Magnetic nanoparticles modified chitosan was used for surfactant capture and analysis using SALDI-MS [166]. Chitosan can be modified with thymine to enable specific preconcentration of mercury (II) before analysis using SELDI-MS [167]. It can be used as a porogen for creating mesopores inside microporous materials [168]. The created hierarchical porous materials can be then used for oligonucleotide delivery offering efficient gene treatment. Chitosan mitigates the toxicity of CdS QDs offering efficient drug delivery of the anticancer drug sesamol [141].

Metal-organic frameworks (MOFs)

MOFs advanced several applications including biosensing [169–172]. Lanthanide MOF was reported for the detection of ferric ions and vitamin C [173]. The material was stable and can form high dispersion with high fluorescence emission signals. Fe(III) ions can selectively quench the fluorescence signal enabling a linear relationship in the concentration range of

16.6–167 μM with a limit of detection (LOD) of 16.6 μM (S/N ratio of >3) [173]. Explosive materials such as nitroaromatic was detected using Zn-MOF [174].

A composite of hierarchical porous bimetallic of (Co, Zn)-ZIF-8, and semiconductor photocatalyst TiO_2 (Co@ZIF-8/TiO_2) was reported for hydrogen generation via photocatalytic water splitting [175]. Co@ZIF-8/TiO_2 showed a photocatalytic hydrogen generation rate of 13 mmol•h^{-1}•g^{-1} representing a 151-fold high catalytic performance of pristine TiO_2 [175]. Co@ZIF-8 improved also hydrogen generation via the hydrolysis of $NaBH_4$ [176]. Carbonized MOF enabled selective dehydrogenation of isopropanol [177].

We reported several procedures to prepare hierarchical porous zeolitic imidazolate frameworks (ZIFs)[178,179]. Template-free and template-based procedures were reported [180]. Dye encapsulation and one-pot synthesis of hierarchical porous (microporous–mesoporous) ZIF-8 were reported for CO_2 sorption and adenosine triphosphate biosensing [181]. A cobalt ZIF material, ZIF-67, was used for hydrogen generation via the hydrolysis of $NaBH_4$ [182,183]. The generated hydrogen can be used for dye degradation [182]. ZIFs-based materials were reviewed as efficient adsorbents and catalysts for CO_2 removal via adsorption and conversion into value-added compounds [184–188]. ZIF-8 and ZIF-67 can be in-situ grown into cellulosic filter paper that was used as an efficient catalyst for the reduction of water pollutants such as nitrophenols [189]. Our synthesis procedures offered several advantages including the formation of a hierarchical porous structure with fast and potential to use for large-scale production [190].

ZIFs materials including ZIF-8 are biocompatible materials [191]. Thus, ZIF-8 was widely used for biomedical applications [192] including gene delivery [193]. However, our recent study showed the transfer of the metal ions into the environment that caused a significant effect on the colonization and decomposition of shaded outdoor mice carrions by arthropods [194].

A zirconium-based MOF, UiO-66, can enhance bone generation offering induction of bone defects in rabbit femoral condyles [195]. UiO-66 catalyzed the hydrogen formation via the hydrolysis of $NaBH_4$ [196]. It was also reported as a precursor for the synthesis of $ZrOSO_4$@C for hydrogen generation [197] and dimethyl ether formation [198].

A cerium MOF (Ce-MOF) exhibited Fenton-like properties that enabled catalytic oxidation of olefins, alcohol, and dyes degradation [199]. It offered 100% and 53% conversion of cinnamyl alcohol and styrene, respectively. It provided high selectivity of 75% and 100% towards styrene oxide and benzaldehyde, respectively. It can catalytically degrade organic pollutants such as dyes [199]. Ce-MOF was also used probe for fluorescence detection of ferric ions and hydrogen peroxide [200], and MOFZyme for the inhibition of fungi [201,202].

A copper-based MOF (Cu and 1,4-benzene dicarboxylic acid as metal nodes and linker, respectively) was in-situ grown into the fiber of cotton textile via a solvothermal procedure [203]. CuBDC@Textile was investigated as a solid sensor and adsorbent for volatile organic compounds (VOCs). It offered selective detection of pyridine via the colorimetric method. Pyridine turned the turquoise color of the prepared materials into deep blue color. It offered a pyridine adsorption capacity of 137.9 mg/g [203]. Lanthanide MOFs were also incorporated into cotton textiles for the photodegradation of stains for smart textiles [204].

Three-dimensional (3D) printing can be used to proceed MOF materials such as leaf-like zeolitic imidazolate frameworks (ZIF-L) into 3D objects with custom porosity and dimension (**Figure 4**)[157]. Direct ink writing (DIW) or robocasting was used to proceed with the materials. The printed materials with a ZIF content of 84% were achieved. The materials can adsorb CO_2 and heavy metals. 3D CelloZIF-L exhibited adsorption capacities of 0.64-1.15 mmol/g for CO_2 gases at 1 bar (0 °C). They showed adsorption capacities of 389.8-554.8 mg/g for Cu^{2+} ions with a selectivity of 86.8% toward Fe^{3+} ions [157]. A filter paper containing cellulose and ZIF-8 were reported [158,159]. The prepared filter paper, denoted as CelloZIFPaper, was used for heavy metal adsorption. The materials offered adsorption capacities of 66.2–354.0 mg/g. CelloZIFPaper was also tested as a flexible electrode for toxic heavy metal detection [158,159]. The reader can directly go to our recent Review on the topic of cellulose-MOF composite (denoted as CelloMOF) and their applications [205]. CelloMOF enabled multifunctional applications being efficient adsorbents and catalysts [156]. ZIF-8 was also reported for the recovery of rare-earth elements [206].

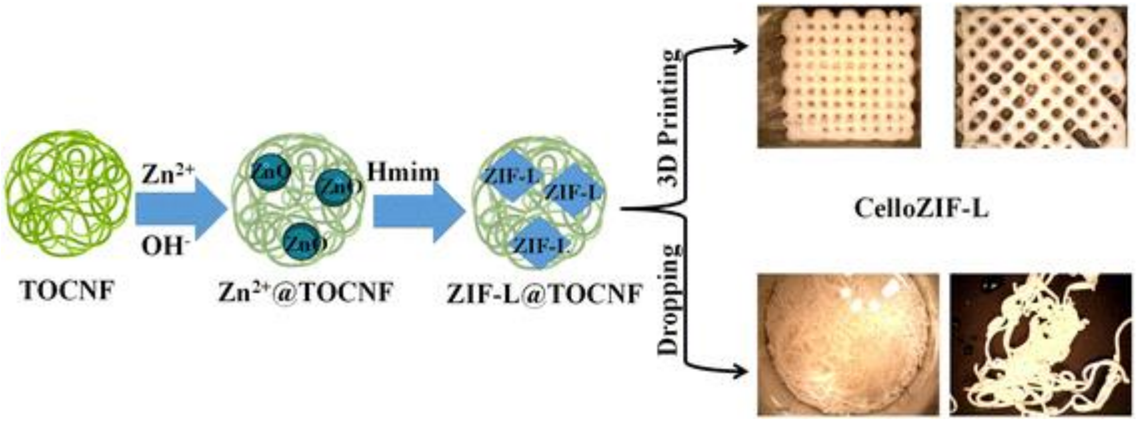

Figure 4 Schematic representation for the synthesis of ZIF-L in TEMPO-oxidized cellulose nanofibers (TOCNF) and 3D printing into cubes and filaments. Figure reprinted with permission from Ref. [157].

Magnetic nanoparticle-modified MOF materials were reported for heavy metal adsorption and removal [207]. Fe_3O_4@ZIF-8 and Fe_3O_4@UiO-66–NH_2) were investigated for the adsorption of Cd^{2+} and Pb^{2+} ions. Fe_3O_4@UiO-66–NH_2 and Fe_3O_4@ZIF-8 offered adsorption capacities of 714.3 mg/g, and 370 mg/g for Cd^{2+}, respectively, and 833.3 mg/g, and 666.7 mg/g for Pb^{2+}, respectively [207].

CuBDC has used the reduction of nitrophenol into aminophenol [208]. CuBDC was used as a precursor for the synthesis of CuO-embedded C i.e. CuO@C [209,210]. CuO@C exhibits a particle size of 36-123 nm [209]. It can be used as an antifungal agent against *Alternaria alternata*, *Fusarium oxysporum*, *Penicillium digitatum*, and *Rhizopus oryzae* with inhibition zones of 36, 20.2, 16, and 10.2 mm, respectively [209]. CuO@C was also used as a photocatalyst for pharmaceuticals e.g. paracetamol degradation [211]. It offered an efficiency of 95% within 60 min [211]. It can also used for the reduction of 4-nitrophenol into 4-aminophenol [212]. In the presence of $NaBH_4$, CuO@C undergo catalytic degradation of organic dyes [213].

ZIF-67 was carbonized into Co_3O_4@N-doped C [214]. The materials after carbonization were used as electroactive material for electrode fabrication. Co_3O_4@N-doped C electrode offered a specific capacitance of 709 F g^{-1} at 1 A g^{-1} [214]. It can be also used as co-catalyst to enahnce the photocatalytic water splitting of semiconductor TiO_2 [215]. ZnO@C was prepared via carbonization of ZIF-8 [216]. It was used for supercapacitor [216]. ZIF-8 was used to prepare ZnO@C photocatalyst that can degrade dyes [217,218]. ZnO@C can be also used an efficient catalyst for methanol dehydration forming dimethyl ether that can be used as energy fuel [219].

Covalent Organic Frameworks (COFs)

COFs were used as support for the in-situ growth of palladium nanocrystals (Pd NCs@COF) [220,221]. Pd NCs@COF was used as the catalyst for carbon-carbon coupling reactions with high efficiency and excellent selectivity [220,221]. A composite of COFs material with two-dimensional nanoparticles e.g., graphene oxide, boron nitride, and graphitic carbon nitride (g-C_3N_4) was synthesized via a one-pot procedure [222]. The nanocomposites were used in water treatment via organic pollutants adsorption [222].

COFs have an advanced energy sector [223,224]. A triazine COF was synthesized via in-situ and ex-situ procedures in the presence of graphene oxide (GO, **Figure 5**) [225,226]. The composite was used to synthesize N-doped carbon (N-doped C)/reduced GO (rGO) after carbonization. N-doped C/rGO displayed a specific capacitance of 234 $F \cdot g^{-1}$ at the current density of 0.8 $A \cdot g^{-1}$. The electrochemical performance of two symmetric supercapacitor devices displayed specific energy and specific power of 14.6 W·h·kg^{-1} and 400 W·kg^{-1}, respectively (**Figure 5**) [225]. A one-pot synthesis of COFs/graphitic carbon nitride (g-C_3N_4) nanocomposite was also reported in our lab [227,228]. The synthesis procedure involved the polycondensation of melamine and benzene-1,3,5-tricarboxyaldehyde in the presence of g-C_3N_4. COF/g-C_3N_4 was used as a precursor for the synthesis of N-doped carbon and N-doped carbon/g-C_3N_4. The prepared materials were used as electrode materials for supercapacitors and lithium-ion batteries (LIBs). COF, COF/g-C_3N_4, N-doped carbon, and N-doped carbon/g-C_3N_4 exhibited specific capacitance of 211, 257.5, 450, and 835.2 F·g^{-1}, respectively. N-doped carbon/g-C_3N_4 was used to assemble asymmetric devices that offered energy density and power density of 45.97 Wh·kg^{-1} and 659.3 W·kg^{-1}, respectively [227,228].

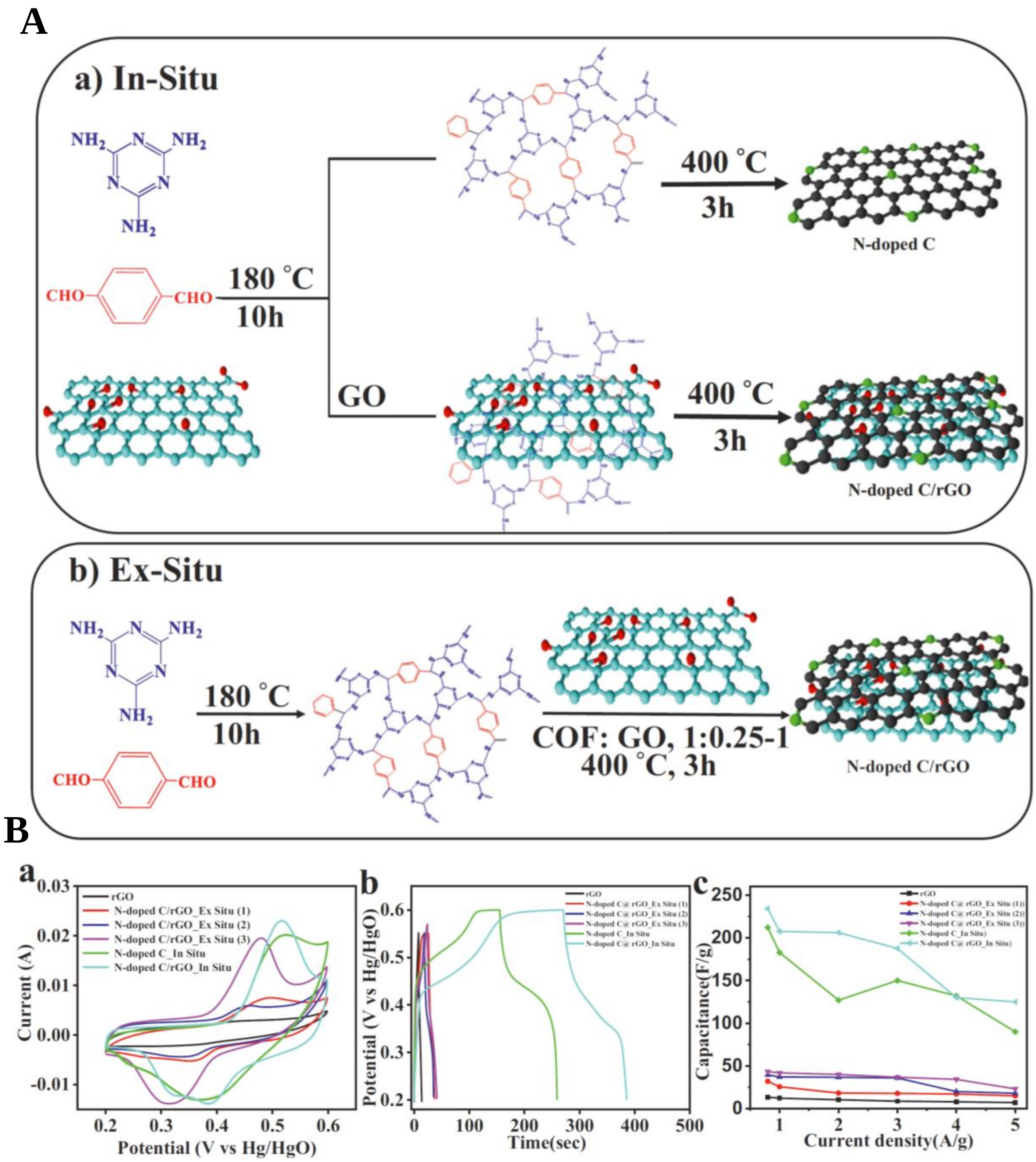

Figure 5 A) Synthesis procedure of the materials and B)electrochemical performance of the prepared electrode using a) CV curves at 50 mV s scan rates b) GCD curves, and c) capacitance over current density. Figure reprinted with permission from Ref.[225].

Conclusions

I summarized the potential of our laboratories to be applied in several fields such as environmental trends e.g., water remediation, air purification, and gas storage; energy e.g., production of hydrogen, dimethyl ether, solar cells, and supercapacitors; and biomedical sectors e.g., sensing/biosensing, cancer therapy, and drug delivery. We can synthesize materials that can be used as efficient adsorbents and catalysts to remove emerging contaminants such as metals, dyes, drugs, antibiotics, pesticides, and oils in water via adsorption. The materials can be also used as catalysts for pollutants degradation, synthesis of new organic compounds, reduction, and oxidation of organic pollutants. They have been applied as filters for air purification by adsorption of greenhouse gases such as carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter (PMs). They can be used for hydrogen production via water splitting, oxidation of alcohol, and hydrolysis of $NaBH_4$. They can be applied for biomedical applications such as antibacterial, drug delivery, and biosensing.

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