Transition-Metal-Based Zeolite Imidazolate Framework Nanofibers via an Electrospinning Approach: A Review

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ABSTRACT: Zeolite imidazolate frameworks (ZIFs) are a subclass of metal organic frameworks (MOFs) and have been considered as a special finding in the current platform of the research arena. ZIFs have been comprised of metal ions with imidazolate linkers. In recent times, ZIFs have been predominately utilized for various applications. This excellent feature is because of its fascinating properties. During the evolution of the materials era, one-dimensional (1-D) fibrous materials are also considered as an important area of research. In order to make the fibrous materials, electrospinning (ES) is considered as a more reliable way for their synthesis. 1-D material has also been utilized for various applications owing to their abnormal physicochemical properties. In this mini-review, the recent developments with various processes have been followed for the synthesis of ZIF materials and 1-D fibrous materials. We elaborated their advantages over their applications in the past years which are discussed and reviewed. More importantly, we have proposed a new area for the incorporation of transition-metal-based ZIF materials into the 1-D fibrous materials, which confers the new direction to the research community to explore its use in various applications.

1. INTRODUCTION

Materials are considered as a vital tool in any kind of research applications. For many years, porous materials have dominated many research fields owing to their utilization and also their uniqueness in properties such as high surface area and tunable porous size nature. However, metal organic frameworks (MOFs) have been considered as a novel area of research, and their hybrid nature of organic−inorganic moieties has been highly noticed by researchers. The term MOFs was introduced by Yaghi and co-workers in 1995.1 MOFs have been utilized for various applications owing to their notable properties such as porosity, low density, crystal volume, high surface area, and biodegradability. For synthesizing MOFs, the protocol is creating an ordered structure that can possess strong bonds between inorganic and organic linkers. So, reticular methods are highly preferred for synthesizing MOF-based materials. Chemical and thermal stability of the MOFs is very high, and this could be attained by strong bonds which are comprised of MOFs. Owing to that, it can withstand a temperature up to 500 °C.2 From the aforementioned evidence, the application of the MOFs is also superfluous which includes separation of gases, molecular separation, chromatography, heterogeneous catalysis, fuel cells, drug storage, drug delivery, sensing, and imaging. One of the phenomenal advantages of MOFs is tuning the structural property by applying the concept called secondary building units (SBUs), wherein the metal clusters have been combined with various functionalities through polytopic linkers.1

Zeolite imidazolate frameworks (ZIFs) have gained more attention in recent years.1 ZIFs have played their role from the beginning of the 1980s when the well-known aluminosilicates emerged, followed by transition-metal-based phosphate and aluminophosphates which enriched interest in the zeolites tremendously in the later 1990s. ZIFs are considered as a subclass of MOFs, and the topology has been similar to zeolites.3

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This normally consists of tetrahedrally coordinated metal (M) ions which are coordinated with an organic imidazolate (Im) linker (M−Im−M). Owing to this coordination, this exhibits unique structures of ZIFs, and different crystal structures with molecular depictions have been given in Figure 1.\(^7\) ZIF materials combined with MOFs have shown the properties of crystallinity, porosity, and enthralling chemical and thermal stability. Owing to the aforementioned properties, ZIFs are also utilized in many fields. Due to the exploration of the various materials, one-dimensional (1-D) materials also joined hands in the field of materials chemistry.

1-D materials are highly desirable owing to their properties and advantages. 1-D materials includes nanofibers, nanowires, and nanotubes. Among them, nanofibers have gained more interest due to their unique properties such as uniform porosity, uniformity in size, unidirectional flow of electrons, and so on.\(^5\) To synthesize nanofibers, there are many methods available: for instance, template synthesis, chemical vapor deposition (CVD), the solution growth method, and the electrospinning (ES) method. Considering the aforementioned processes, many require careful handling, high cost, and highly sophisticated instrumentation. However, the electrospinning method has been considered as the most reliable and one of the pioneering methods to synthesize stable continuous fibrous material.\(^6\) Owing to their excellent properties, this has been utilized in many fields such as nanotechnology, biomedical, defense, tissue engineering, biotechnology, and filtering applications. By combining transition-metal-based ZIFs with 1-D fibrous materials, this will give combined properties with improvised applications, and also this will give the future directions to explore more in the field of material chemistry.\(^7\)

In this mini-review, we have discussed the recently achieved developments, and some future directions have been added in the field of material chemistry. It is separated into three parts: first, we elaborated on the common synthetic methods available for preparing ZIFs and the advantages of using ZIFs with their
application, followed by the synthetic importance of ES techniques for the synthesis of 1-D fibrous material and their advantages over applications. For a future perspective, a new area of finding the incorporation of transition-metal-based ZIFs onto the 1-D fibers and their advantages with required developments are also discussed and concluded.

2. TYPES OF ZEOLITE IMIDAZOLATE FRAMEWORKS (ZIFs)

Zeolite imidazolate frameworks (ZIFs) have emerged as a unique class of metal organic frameworks (MOFs) which are built with imidazolate liners. These kinds of MOF materials have exhibited more distinct properties than other MOFs. According to their properties and flexibility on functional group substitution, more than 150 structures have been explored, enabling the aid of diverse topological behavior with obtained structures, owing to the nature of the ZIFs, which has been broadly classified into powder-based ZIFs and membrane-based ZIFs. The classification of their types and various synthetic processes has been summarized and shown in Figure 2, and the detailed discussions have been elaborated on below.

2.1. Synthesis of Zeolite Imidazolate Frameworks (ZIFs)

2.1.1. Powder-Based ZIFs. ZIF materials most commonly exist as a powder form which was utilized after the impurities had been separated from the reaction mixture. Under this, according to their preparation methods, two important classifications were observed as synthesis with the aid of solvent and the solvent-free synthesis process, but the observed resultant materials had equal importance in various applications.

2.1.1.1. Hydrothermal Method. Recently, the hydrothermal method for synthesizing ZIFs has become highly preferred, wherein water as a solvent has been utilized for the facile formation of various types of ZIFs. The ZIFs with different metals can be taken for the facile formation of organic—inorganic ZIF networks. With the change in reaction conditions, temperature, and time, it can formulate different ZIF coordination structures. For example, Miyake et al. synthesized pure ZIF-8 crystals in an aqueous system and reported that at room temperature the crystalline ZIF-8 could be formed. By improving the hydrothermal activity, Liu et al. reported that ZIF-8 was synthesized under hydrothermal conditions and was capable of showing high water resistance after a shell—ligand exchange reaction, where the structural aspects of the ZIF-8 were also well retained (Figure 3).

For a water-based system, in order to improve the ZIF formation and also to reduce the use of ligand formation, deprotonating agents have been used as additives. Most commonly, ammonium hydroxide has been utilized which could directly arbitrate on the structural formation of ZIFs. The solvothermal method was considered as one of the highly followed conventional methods compared to all other available methods. Here, organic solvents such as methanol, ethanol, and isopropanol alcohol have been broadly occupied for these aspects of ZIF preparation. Although organic solvents give considerable product formation, due to their high cost and flammable nature. But, it is highly dangerous to our ecosystem. Jeong et al. carried out utilization of the in situ counter-diffusion method for the formation of ZIF-8 membranes where zinc was deposited over porous alumina support followed by 2-methylimidazole solution, and then the diffusion of ZIF-8 from the support under the solvothermal synthesis for 4 h at 120 °C. The
synthesized ZIF-8 membrane has shown superior separation performance. The detailed mechanism has been displayed in Figure 4.

2.1.1.3. Ionothermal Method. Recent developments were observed in the case of ZIF-based material preparation. One of the better ways for the synthesis of ZIF is the ionothermal method. Ionic liquids such as 1,3-dialkylimidazolium cations, tetrafluoroborate ($\text{BF}_4^-$) anions, and hexafluorophosphate ($\text{PF}_6^-$) anions have been utilized as both solvents and templates for the preparation of ZIF materials by the ionothermal method. Moreover, ionic liquids are utilized for the preparation of a eutectic mixture from which ZIFs have been derived. In order to avoid their competitive interaction, the hydrothermal route has been chosen for the synthesis of ZIFs. Their advantages allow them to undergo open atmospheric synthesis also. One of the greater advantages engaged in ionic liquids is the recyclable nature for further usages.\(^1\)

2.1.1.4. Mechanochemical Method. The mechanochemical method has been considered as a greener and also solvent-free way to construct a ZIF material, wherein ZIFs have been synthesized via a mechanochemical approach more suitably by the ball-milling method. However, limitation occurred by utilizing oxide-based materials for the synthesis of ZIFs. In order to overcome this issue, Friscic et al. introduced a modified way of synthesis called a liquid-assisted grinding and ion- and liquid-assisted grinding method for the synthesis of ZIFs using metal oxide ZnO with other ligands. In room-temperature synthesis, the addition of the liquid phase could significantly increase the mobility of the ions.\(^1\)

As a further advancement, solventless conversion of ZnO to ZIF-8 by using a simple ball milling method has been reported by Tanaka et al. where ZnO salt is mixed with a methylimidazole ligand under ball milling conditions. At the end of the process, larger size particles confirmed the presence of ZnO, but smaller
sized nanoparticles confirmed the formation of ZIF-8 as given in Figure 5.12

2.1.2. Membrane-Based ZIFs. Membrane-based ZIF materials are highly desirable owing to their abnormal properties. After the utilization of the powdered ZIF material, membrane-based materials were largely utilized in the field of gas separation and catalysis and so on. The intrinsic activity of this material could give an immense category compared to others. Membrane-based ZIFs are broadly classified by the ZIF membranes and ZIF composites.

2.1.2.1. Crystallization Method. For the synthesis of membrane-based ZIF materials, the recommended method of synthesis is the crystallization method which includes both secondary growth crystallization and in situ crystallization. The secondary growth crystallization technique follows deposition or pretreatment. For these processes, the notable techniques are the dip coating and seeded growth method. The gaps observed on the membrane have been nullified by the growth of seeds internally which leads to the formation of a continuous membrane. Also, the advantage over the seeded growth method is that the orientation of the membrane has been controlled throughout the process, which includes membrane thickness and grain size.1 Up to now, ZIF membranes have been utilized for only a smooth molecular sieve effect for the separation of lighter gases such as H₂, CO₂, and CH₄. However, in their study, they demonstrated that the ZIF-8 membrane had shown a sharp molecular sieve separation on H₂/C₃H₈ also.

2.1.3. Applications. Transition-metal-based ZIF-derived materials have been utilized in many fields, owing to their notable properties such as uniform porosity, flexibility toward substituents, numerous compositions, and most importantly physical and chemical stability. Depending on the area of interest, ZIFs and their composites/membranes have been utilized for specific application. Some of the important applications are highlighted in this session.

2.1.3.1. Energy Storage Devices. In recent years, energy storage devices such as batteries and supercapacitors are in high demand. Rechargeable batteries are majorly categorized into lithium ion batteries (LIBs), lithium sulfur batteries (LSBs), and supercapacitor.13–16 An electrode with improved electrochemical behavior is required to fulfill prerequisites of a conventional battery. To take over this issue, transition-metal-based ZIF-derived materials can be potentially utilized as an electrode material for energy storage devices. Zhang et al. developed a new route to grow ZnO@ZnO QDs/C NRAs on carbon cloth substrate by utilization of ZIF-8 material and applied as an anode for LIBs. The material showed high specific capacity and excellent stability over multiple cycles.17 Due to the improvised electrochemical performance of ZIF-derived materials, they can be utilized for other types of batteries as well.

2.1.3.2. Gas Separation. For the separation of gases, pure ZIFs and their composite/membrane have been considered as highly recommendable, owing to their properties such as tunable porosity, flexibility over substituents, various structures, and multiple chemical functionalities. CO₂ adsorption/separation is an expanding area, wherein pure CO₂ has been adsorbed, but in the case of CO₂ separation it is associated with other gas systems such as CO₂/N₂, CO₂/H₂, and CO₂/N₂. The crystals inside the ZIF materials are capable of adsorbing CO₂, where ZIFs can provide Langmuir sites. These sites have been replaced by the adsorbed CO₂ molecule. Song et al. synthesized a membrane-based ZIF-8 nanoparticle dispersed through the polymer. This membrane can enormously increase the permeability of CO₂ on gas absorption tests, which could clearly show that the loading of ZIFs significantly influences the permeability of CO₂.3

2.1.3.3. Drug Delivery. ZIF materials are considered as one of the promising candidates for the drug delivery platform owing to their pH-sensitive properties. ZIF-8 has been utilized as an anticancer agent and is also used to give thermal production for other drugs. ZIF-8 was synthesized by Sun et al. and mixed with anticancer drug 5-fluorouracil (5-FU) (~660 mg of 5-FU/g). They showed that the material had excellent anticancer activity and could be a promising material for the treatment of cancer.18 Adhikari et al. have successfully encapsulated an anticancer drug DOX in ZIF-7 and ZIF-8 and observed that both can act as an excellent drug-releasing property when they made contact with lipid membranes as well as micelles.2

2.1.3.4. Other Applications. Zeolite imidazolate frameworks (ZIFs) have also been utilized in many other fields such as catalysis, sensors, electronic devices, etc. Initially, ZIFs have been considered as a typical aluminosilicate, and their utilization as a catalyst in the commercial sector was enormous. ZIFs are utilized as catalysts for many reactions, and in some cases it has been restored and reused for other reactions. Intrinsic activity, notably textural property, made ZIF a promising material for sensing applications also. The main characteristic properties of tunable pore size and facile functionalization enable them as an attractive material for many applications.1

3. OVERVIEW OF ONE-DIMENSIONAL (1-D) FIBROUS MATERIAL

One-dimensional (1-D) materials are classified as fibers, wires, rods, tubes, and belts in micro- and nanoflows. Owing to their novel properties and applications, much attention has been given for the synthesis procedure to make size-controlled 1-D materials by tuning the chemical composition of the precursor.5 Among the available 1-D materials, fibrous materials are highly desirable. Their properties such as uniform size, unidirectional flow of electrons, and uniform porosity made them an asset to the user. In order to synthesize fibrous materials, plenty of methods are available, notably, the lithography method, solution growth method, roll printing method, chemical vapor deposition method (CVD), template synthesis, and electrospinning method. Among them, electrospinning method has been considered as the most reliable technique for the synthesis of fibrous materials. The electrospinning method has several advantages such as simple handling, cost-effective technique, and more importantly, it results in continuous fiber formation.

3.1. Electrospinning Method. Electrospinning is also called electrostatic spinning. The first device has been demonstrated to spray the liquids through the applied electrical charge. Thus, it was starting to get popularized and also gained academic interest across the world in the 1990s only. Researchers proved the possibility of making fibrous materials using polymer solution under laboratory conditions.7

3.1.1. Principle Behind Electrospinning. Electrospinning is a simple technique, and also we can easily control the production of the fibers into nanometer size in range. At the initial stages, pure polymer solutions have been utilized for the fabrication of fibrous materials. Later, the trend has been improvised into other materials also. The emblematic electrospinning setup has been portrayed in Figure 6. The electrospinning instrument mainly consists of a high voltage power supply, a spinneret, and the conductive collector. The precursor solution was taken into the syringe with a thin nozzle, where the high voltage will be applied, and this serves as an electrode. The working distance of
the nozzle and the counter electrode should be approximately between 10 and 20 cm, although it depends on the precursor materials used in the fiber formation.

By applying voltage, electrospun fibers are deposited on the counter electrode, when the strength of the electric field allows the electrostatic forces to overcome the surface tension of the precursor material. During this process, solvent can evaporate, and the solid fibers are deposited as a nonwoven mat over the collector. The commonly available electrospinning setup has been classified into vertical setup and horizontal setup in Figure 7. Here the applied voltage causes a cone-shaped deformation of the droplets from the polymeric precursor solution. Commonly used water-soluble polymers are poly(vinyl alcohol) (PVA), poly(ethylene oxide) (PEO), and polyvinylpyrrolidone (PVP), and some of the organosoluble polymers such as polyamide (PA), polycarbonate (PC), and polycrylonitrile (PAN) have been utilized for making fibrous materials. The electrospinning process is exclusively governed by many parameters, and the most important parameters are classified into solution parameters, process parameters, and ambient parameters.

3.1.2. Solution Parameters for Precursor Material.

3.1.2.1. Viscosity. The viscosity of the precursor materials is a vital parameter of the electrospinning process. Solution viscosity is the major tool to determine the size and morphological aspect of the fibrous material. It has been found that, for lesser viscosity solution, there is no fiber formation as the quantity of the droplet formation is high instead of fibers.

Also, the surface tension of the solution is the factor which leads to beads or beaded fiber formation. However, in the case of highly viscous medium, the solution was wedged on the pathway of the nozzle. There is an optimal viscosity needed for the continuous fiber formation.6

3.1.2.2. Surface Tension. Solvent composition of the solution furthermore plays an important role in fiber formation. Facile fiber formation has to be confirmed by the reduction of surface tension of the solvent.7 Solvent having higher surface tension directly contributes to the generation of droplets on the collector. Lower surface tension solution helps the process to occur at a lower electric field. Better fibrous performance has been achieved by the lower surface tension solvents.

3.1.2.3. Molecular Weight. The molecular weight of the polymer also plays a major role in determining all the solution parameters such as viscosity, surface tension, and the conductivity of the polymeric solution. It is another important parameter to affect the morphology of the fibrous materials.5 Low molecular weight polymers produce beads rather than the fibrous materials. In this case, the high molecular weight substance tends to give fibrous materials with desired diameter, where the entanglements are numerous. This exhibits sufficient intermolecular interaction which provides high grade uniform fiber with lesser quantity of beads.7

3.1.2.4. Conductivity. The conductivity of the solution is mainly determined by the type of the polymer that has been used as solvent and the quantity of the ionizable salts which are present on the precursor solution. Increasing the electrical conductivity of the precursor solution is significantly decreased by the fiber diameter. In the case of low conductivity polymer solution, due to elongation by the electrical charge, the uniform fiber has been formed, but the quantity of bead formation also becomes very high. However, highly conductive solutions are unstable when a strong electric field is applied and showed the broad diameter distribution and that the size of the fibers is reduced drastically.6

3.1.3. Processing Parameters of Electrospinning.

3.1.3.1. Working Distance. For the fiber formation, one of the major criteria is working distance. The distance between the tip...
and the collector is greatly influenced by the morphology of the sample and diameter. The minimum distance is required for the formation of fibers, and there is a need for sufficient time which is required for the fibers once it is ejected out from the nozzle and in order to get dried. Therefore, the distance should be optimum. Otherwise, the bead formation will be observed even for high and low working distance. The polymers such as PVA and polyvinylidene fluoride (PVDF) have been examined, and it was reported that the morphology has been greatly governed by the working distance.\(^6\)

3.1.3.2. **Applied Voltage.** Applied voltage is one of the most crucial parameters for the fiber formation. The threshold voltage is a necessary factor for the formation of fibers. This voltage initiates the charges through the precursor solution which could end up with the fibers. As per the observation, when the higher voltage is applied on the solution mixture, there is an ejection of polymer, and this should be more, which are frontrunners to the large diameter fibrous materials. Electrostatic repulsion has been observed on the solution which narrows fiber formation in the aforementioned cases.\(^7\) Coulombic forces have been observed on the solution which leads to stretching and affects the fiber diameter. In the case of low applied voltage, the charge is not sufficient to make electrostatic repulsion which significantly affects the fiber formation with numerous amounts of bead formation.

3.1.3.3. **Flow Rate.** Flow rate is the most important parameter which influences the transfer rate of the solution from the syringe. Low flow rate is highly desirable for the fiber formation. So, the optimum flow rate is very important for feasible fiber formation. The slow flow rate influences the fiber diameter and also pore size distribution. Most of the significance of this one is the optimum flow rate that has to give enough time to dry fibers, although a higher flow rate leads to the beaded fiber with unstable morphology.\(^8\)

3.2. **Application.** Owing to their versatile properties and morphological aspects, 1-D fibrous materials have been utilized in diverse fields. Most of the highlighting properties such as high surface to volume ratio and very high porous nature have taken over 1-D materials in more specific applications. Manipulation of the size and morphology can also be advantageous throughout the available areas where application is required. 1-D fibrous materials have been broadly utilized in medicinal applications, filtration, drug delivery, catalysis, defense, and energy storage devices.\(^9\) Utilization of 1-D fibrous materials in various fields has been given as shown in Figure 8. In the case of biomedical application, it includes skin therapy and skin healing, whereas applications in life sciences can be classified as wound dressing, drug delivery, hemostatic devices, and enzyme encapsulation.\(^10,11\) Tissue engineering and scaffolding are comprised of porous membrane materials for skin, blood vessels, and nerve regeneration and 3-D scaffolding for bones. In military protective clothing, it includes effective trapping of aerosol particles and minimal impedance to air and antibiogas prediction. 1-D fibrous materials have been widely used in the field of sensor application where it is categorized to biochemical sensors, piezoelectric sensors, thermal sensors, and optical sensors. Filtration includes water filtration, air filtration, and molecular filtration where 1-D fibrous materials have been utilized in removing oils, proteins, and chemicals, which causes health hazards from drinking water. In the case of industrial wastewater, it will have heavy metals such as lead, zinc, copper, cadmium, mercury, and chromium contamination and has been controlled by 1-D fibrous materials. In air filtration technology, it has been utilized as high efficiency particulate air (HEPA) filters which are made up of microsized fiberglass, which is intended to remove the tiny particles present in the atmosphere.

4. **INTEGRATION OF ZIF INTO 1-D FIBERS**

Incorporation of ZIF into the 1-D fibrous materials has given great advantages to the scientific research community. Herein, the synthesis of the 1-D fibrous materials with ZIF and the advantages along with their properties and advantages associated with the application and the future directions and challenges have been discussed.

4.1. **Synthesis of the 1-D Fibrous Materials with ZIF.** In a typical synthesis, ZIF materials have been prepared through the available methods such as hydrothermal, solvothermal, and related synthetic methods as described above, and the synthesized material was well characterized according to their size, morphology, and elemental state. In addition, the use of suitable conductive polymers has been chosen for making a polymeric solution using appropriate solvent. ZIF mixtures are quantified and mixed with a suitable polymer which has been mixed apparently with suitable requirements as we discussed in the solution parameter part. At the time optimum viscosity is observed, the solution is ready for further proceedings. Next, the processing parameters of the electrospinning have been optimized in accordance with the solution viscosity. The desired fibers have been formed, and the resultant fiber is well characterized and utilized for application processes.

4.2. **Advantages and Applications.** Incorporation of ZIF materials into the 1-D fibrous materials has finer advantages in the aspects of many fields due to their fascinating properties. ZIF has the most important properties of highly porous material nature and abnormal thermal stability. In the case of 1-D fibrous materials, they exhibit many properties such as uniform porosity, unidirectional flow of electron, uniform size, and unique physicochemical properties. Another important condition in electrospinning is tunable size and the porosity. A combination of these two material properties has given a greater opportunity to explore more in the aspects of applications by the research community.

For example, Chen et al. have synthesized hollow particle-based N-doped carbon nanofibers by simple carbonization treatment of ZIF-8/PAN composite materials as a precursor for the electrospinning process. The hierarchical porous nanofibers have been utilized as an electrode for the supercapacitor and in turn showed outstanding cycling stability of only 1.8% capacitance loss over 10 000 cycles.\(^12\) Liu et al. synthesized a

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**Figure 8.** Applications of 1-D fibrous materials in various fields.
Co–Zn-based porous 1-D fiber having large surface area with high porosity. Owing to this advantage, it showed good activity in oxygen reduction reaction (ORR).\textsuperscript{22} Zhang et al. have synthesized electrospun-ZIF-67 NPs followed by a thermal treatment, giving Co$_3$O$_4$ hollow nanoparticles (NPs). Owing to their unique structural feature, synthesized materials have been utilized as an anode for LIBs and shown excellent electrochemical behavior.\textsuperscript{23} Recently, we have synthesized electrospun Co-ZIF microfibers (Figure 9), and the corresponding field emission scanning electron micrograph (FESEM) images are given in Figure 10. Here, the metal particle present on the fiber has been exposed over the surface of the fibrous material. This has been utilized as a catalyst for oxygen evolution reaction (OER) in 0.5 M H$_2$SO$_4$. Among the different samples analyzed, Co-ZIF-550-N$_2$ delivered a superior activity with a lower overpotential of 405 mV at a current density of 10 mA cm$^{-2}$.\textsuperscript{24} In 1 M KOH, Co-ZIF-350-Air required an overpotential of 370 mV at 10 mA cm$^{-2}$ and a lower Tafel slope value of 55 mV dec$^{-1}$. In the same way, we have synthesized nitrogen-enriched ZIF-67 -incorporated ZIF-7 microfibers (Figure 11), and the synthesized materials have been utilized as a catalyst for OER in 1M KOH. It was shown that CoZn-ZIF-500 delivered superior activity at a current density of 10 mA cm$^{-2}$ with a lower Tafel slope and explicitly exposed good long-term stability.\textsuperscript{25}

5. SUMMARY AND OUTLOOK

In this mini-review, the origin of the zeolite imidazolate framework, a general synthetic process which is commonly available to synthesize pure ZIFs as well as ZIFs composite, has briefly been discussed. In addition, the application of ZIF materials in various fields with their advantages in terms of properties has been discussed and elaborated on in detail. In the same way, the significance of the 1-D fibrous materials and advantages which are associated with the electrosynmatizing process, important parameters which engaged with making a precursor solution, and also for processing have been detailed, and their advantages and applications have been discussed. Incorporation of ZIFs into the 1-D fibrous materials has been proposed, and some of the applications with their advantages have been highlighted specifically.

ZIF-incorporated 1-D fibrous materials are highly desirable, owing to the combined properties of the materials. In spite of this, there are lots of advantages. Some barricades have been associated with those processes. In the case of ZIFs, we have learned that concepts which are available to synthesize ZIFs but with zeolite chemistry have to be explained and examined deeper in detail. Some of the simple synthetic methods have been started to explore ZIFs with other proposed methods; for example, continuous microfluidic synthesis has been chosen to tune the pore size of the zeolites in ZIF preparation. For some applications, powdered ZIFs should be shaped into pellets, and for that some backlogs have to be rectified. Specified applications need hierarchical superstructures of ZIFs, but that is still being used at a moderate level. Most importantly, for commercial applications, a cost-effective technique has to be explored for laboratory to large-scale industries. In the case of composite materials, the materials which are coordinated with the ZIFs are not appropriate; however, an adequate assessment should give new opportunities and also new insights for the exploration of ZIF synthesis.

A lot of improvements have been observed in the case of synthesis of 1-D fibrous materials in the electrosynmatizing process such as coaxial electrosynmatizing, mixing and multiple electrospinning, core–shell electrosynmatizing, etc. These innovative findings gave an immense improvement in the electrosynmatizing...
process. For instance, there are some polymers for which it is difficult to make fibers by utilization of the aforementioned techniques that have been achieved. However, some improvement is needed for the synthesis process. Solution viscosity is the major issue for controlling the size. To control the defect and beads on the fibers, these are still crucial for some cases. More importantly, incorporating metal and metal oxides on the fibrous structure is problematic and challenging where size is found to have a major role for this process. The chemistry behind the electrospinning should be improved for attaining an exact composition and feasible fiber formation. Incorporating other morphological structures into the fibers is also a most challenging one. In order to ensure the desired properties from the morphology and various structures, a new development will be attained in the near future. As per all the evidence, in future perspective we can highlight the following important points:

- There are numerous types of ZIFs that could be identified by utilizing their structural flexible properties via unique synthetic approaches. Then the newly formed ZIFs can be made as fibers with different nominal lengths via an electrospinning approach.
- These 1-D fibers made through the electrospinning method can be explored in different fields of interest due its flexible nature and stability.
- By tuning the incorporation of metals into ZIFs structures and concentrations, polymers used can vary the nature of resulting fibers, and this will be a new finding to further explore the area of materials chemistry.
- Owing to the advantages, ZIF-incorporated 1-D fibers via the electrospinning approach will be a promising candidate for widespread applications in various fields such as the 1-D nature of fibers formed and the nature of ZIFs taken for fiber formation.

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**Notes**
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