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Thesis Conclusion

In this thesis, we have explored fabrication of various multiscale functional platforms and investigated the applications of these functional platforms towards sensing, and environmental remediation. The major outcomes and the future aspects from each of the investigations are summarized below.

Chapter 1. The integration of microsystem technology with nanotechnology has enabled the development of miniaturized systems with enhanced functionalities. These advances facilitate the design of functional platforms capable of detection of specific analytes, ensuring environmental and human safety, and efficient remediation of wastewater, including the removal of carcinogenic dyes and oily pollutants.

Chapter 2. Nano-structured, flexible platforms show high potential in gas monitoring, environmental remediation, and health diagnostics. Further the integration of machine learning algorithms and nanotechnology promises the transformative advancements, driving faster materials optimizing at nanoscale manufacturing, thus enhances their advanced application in sensing, and foster their sustainability. The fabrication of a flexible hybrid nanostructured platform combining ZnO, TiO_2, and PEDOT:PSS nanomaterials, exhibits a significant improvement in detecting trace levels of H_2 gas at low temperatures. Furthermore, the ternary nanocomposite-based sensor demonstrates selectivity towards H_2 over CO_2, NH_3, and CH_4, achieving a LOD of ~9 ppt. Thus highlights the potential of the developed hybrid nanostructured platform and ternary nanocomposite-based device for monitoring trace levels of H_2 gas, particularly in industrial applications.

Chapter 3. The fabrication of low costs and room temperature operated flexible nanosensor is highly desirable for healthcare monitoring. To overcome this, the La doped ZnO-MWCNTs nanocomposites based flexible CO gas sensor is fabricated. At 27°C, the prepared sensor responded 8 times faster than La-ZnO to 100 ppm CO gas. The sensor also demonstrated an humidity tolerant properties with good selectivity and can detect low CO concentrations of 100 ppb. Furthermore, in healthcare diagnostics, a flexible MWCNTs/Nb_2O_5 based nanosensor was successfully fabricated to distinguished diabetic from non-diabetic breath samples through acetone detection. Further the developed nanosensor features fast response, stable, and precise signals, showing promise for non-invasive diabetes monitoring. In addition, the sensor demonstrated an enhanced response/recovery time of the sensor was 25/46 sec, respectively with a limit of detection of 330 ppb operating at RT.

Chapter 4. Hybrid and hierarchical nanocomposites improved sensitivity, selectivity, and stability at low temperatures. These nanostructures are effective for detection of uric acid and a trace-level detection of flammable gases like H_2, making it ideal for bio/gas sensing at ambient temperatures. Moreover, the use of biodegradable substrate (such as disposable paper and natural polymer) has opened a way for improved scalability, and affordability in the advanced sensing technologies.

Chapter 5. The fabrication of multiscale platform by intergrading additively manufacturing and nanotechnology have demonstrated an exceptional method for advanced applications such as gas sensing and wastewater remediation. The prepared PANi@ 3D PyC platform was used for NO_2 gas sensor. The PANi@ 3D PyC sensor demonstrated an excellent response to NO_2 gas and operates effectively at RT, mitigating energy consumption, device

instability, and operational risks due to elevated temperatures. It exhibited strong repeatability with rapid response and recovery times of 36 sec and 59 sec, respectively, and a notable LOD of ~700 ppb. In the next work, ZnO nanowires decorated PyC platforms achieved photocatalytic degradation (~84%) of RhB dye under sunlight. Further demonstrating the importance of integration of advanced microsystems in solar-driven photocatalysis that offers an on-site sustainable approach for efficiently degrading wastewater contaminants.

Chapter 6. The fabrication of polymeric platforms using soft lithography has demonstrated an economical approaches for degrading commonly used textile dyes. These microsystems opens up new possibilities for flexible and biocompatible environmental remediation solutions. Furthermore, these studies might well assist future researchers in better understanding the relationship between both designing functional microsystems and their photocatalytic degradation. The decoration of dense growth of the Au sputtered ZnO NWs on PDMS tubes were responsible for delivering a high surface-area-to-volume ratio. The entire degradation of RhB dye took ~330 mins with the ZnO-Au hybrid wires. In the next research approach, we fabricated a lotus-like microstructure replicated on PDMS coated with Ta-ZnO composites. Further, a real-time MB dye degradation is also monitored using the IoT technique by integrating a NodeMCU microcontroller board as a control center and a pH sensor as a tool for detecting the change in pH value of the MB dye. The photocatalytic reaction of the Ta-ZnO NWs composite coated PDMS tube took 105 mins, which is faster than ZnO. These photocatalysts lead to "waste control using Ta-ZnO NWs composites," which opens up new possibilities for flexible and biocompatible environmental remediation platforms.

Chapter 7. The fabrication of multiscale engineered platforms using combination of electrospinning, carbonization, and soft lithography have demonstrated an economical approaches for removal of oil/water separation and degradation of textile dyes. The prepared TiS_2/CS:CNF membrane had demonstrated an exceptional hydrophobic and oleophilic characteristics, with a water contact angle of ~133˚ and an oil contact angle of ~3˚**,** respectively. Different oil samples such as gasoline, diesel, turpentine, and castrol oil were mixed with water and were subsequently separated using an experiment namely, gravity-driven and tilted oil/water separation. The experimental results suggest that an oil/water mixture can be effectively separated using any oil with low absolute viscosity. In the next work, we decoration of a Ficus religiosa leaf mesh with a hybrid nanocomposite for simultaneous oil/water separation and wastewater degradation. The experimental results suggest that an oil/water mixture can be effectively separated using any oil with low absolute viscosity. Moreover, in the presence of sunlight, the ZnO/PANi@PMMA coated leaf mesh degraded the MO dye solution in 140 mins with a maximum ~91% degradation efficiency. Next work demonstrated a use of cost-effective method for fabricating an optofluidic microreactor, featuring graphene QDs@MOF(Ti) photocatalyst decoration within the channels for MB dye degradation. The direct integration of graphene QDs@MOF(Ti) into the microchannels ensures intimate contact with the MB dye solutions, minimizing interaction time and maximizing purification efficacy of ~99% under visible light exposure at a flow rate of 50 µL min^{-1}. These advancements underscore the remarkable potential of these low cost multiscale functional platforms for practical wastewater treatment applications.

Scope of Future Work

1. The integration of multiscale functional platforms with Internet of Things (IoT) networks can enhance their portability and enable real-time monitoring of toxic gases. This integration will further support the development of smart nano sensors, ensuring rapid detection and response to hazardous situations in industrial, urban, and residential settings.
2. Expanding nanostructured sensor research to detect other biomarkers, such as ammonia and methane in exhaled breath, holds great potential for non-invasive disease diagnosis.

This approach offers significant benefits in healthcare by facilitating early detection and continuous monitoring.

3. For wastewater remediation, nanomaterials should be designed and optimized to operate effectively in the near-infrared region, allowing them to fully utilize the potential of direct sunlight-driven photocatalysis.
4. Investigating the lifecycle of nanostructure-decorated functional platforms can enable the design of safer and more sustainable nanomaterials for both sensing and remediation applications.

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