Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Smart Sensing Materials: The Evolution of Trace Moisture Detection

Ronak Ali (Corresponding Author)
The Benazir Bhutto Shaheed University of Technology and Skill Development, Khairpur Mirs, Sindh, Pakistan. baladironak@gmail.com

Ayaz Ali Mandan
The Benazir Bhutto Shaheed University of Technology and Skill Development, Khairpur Mirs, Sindh, Pakistan

Shafquat Rasool Tumrani
Shah Abdul Latif University, Khairpur Mirs, Sindh, Pakistan

Izhar Hussain
The Benazir Bhutto Shaheed University of Technology and Skill Development, Khairpur Mirs, Sindh, Pakistan

Ghalib Raza Solangil
The Benazir Bhutto Shaheed University of Technology and Skill Development, Khairpur Mirs, Sindh, Pakistan

Muzammil Hussain Wadho
The Benazir Bhutto Shaheed University of Technology and Skill Development, Khairpur Mirs, Sindh, Pakistan

Muhammad Waqas Soomro
Sukkur IBA University, Sukkur, Sindh, Pakistan

Madad Ali Shah
Shaheed Benazir Bhutto University, Shaheed Benazirabad, Sindh, Pakistan

ABSTRACT

In this paper, recent developments of ultra-low humidity sensing are reviewed, comparing high performance nanomaterials to the conventional matrices. For ultra-dry conditions (0.1 to 12.0% RH), special configurations are required such as defect engineered TiO2/Sn2 heterostructures grown by atomic layer deposition, in-situ grown metal-organic frameworks (MIL-101-Cr), and inkjet-printed 2D Graphene Oxide/MXene layers. Tracking mass changes in absolute value is achieved with the use of mesoporous carbon with carboxyl functional groups (FDU-15-COOH) on quartz crystal microbalance resonators, providing hysteresis-free sub-parts-per-million detection. They are able to deliver a much better performance compared to the well-

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

known polymer and cellulose matrices, where the swellable chain networks cause a very high hysteresis (up to ~17.3% water) due to water penetration. In addition to material engineering, gas calibration systems for divided-flow gas sensors and evaluation metrics, such as sensitivity, hysteresis and response/recovery time, provide the accuracy of the trace moisture sensors. Lastly, this paper provides a survey of the most recent advances in engineering that are reshaping raw drifting sensor data into intelligent networks. Smart sensing systems, that incorporate machine learning calibration algorithms on edge microcontrollers, localized micro-heaters for thermal self-regeneration and low-power distributed IoT architectures (such as LoRaWAN, Zigbee), have successfully addressed thermal drift, recovery lag and environmental poisoning, allowing continuous spatial monitoring in critical industrial applications.

Keywords— Ultra-low humidity sensing, Defect engineering, Metal-organic frameworks (MOFs), Edge-AI calibration, and Distributed IoT architectures**.**

1. Introduction

The metal oxides with defect engineering, highly stable devices include the TiO2/SnO2 heterostructure [1-9]. It is fabricated by precisely depositing materials using Atomic Layer Deposition (ALD) [10-19], followed by high-temperature thermal calcination [20-28] and is of a resistive transduction mode. Since the film thickness and composition can be controlled at sub-nanometer level, it is expected to be able to introduce high density of oxygen vacancy defects. The vacancies are deep Lewis acid motifs which bind trace water molecules at sub-10%RH with a very high sensitivity of ΔR/R0=154 per /%RH, and they maintain a minimal hysteresis below 1.8%.

A different type of structure is the porous crystalline frame structure which is grown in-situ on sensor electrodes via a sol-gel hydrothermal process in the presence of the hydrophilic Metal-Organic Framework (MIL-101-Cr) [29-35]. The method generates a highly porous network with crystallographically oriented micropores that have a kinetic diameter corresponding to that of the water molecule. This framework works in a capacitive range between 0.5% and 12.0% RH, and has a very large specific surface area, enabling it to quickly capture trace moisture, which boosts the sensitivity to 45.2 pF/%RH with a well-controlled hysteresis limit (<2.1%).

In low-dimensional architecture (Figure 1), the matrix shows a high-resolution inkjet-printed Graphene Oxide (GO)/MXene heterostructure [36-41]. The approach allows for patterning with no masks and at scales both rigid and flexible. The sensor is comprised of stacked 2D layers, which take advantage of interfacial charge transfer and quantum tunneling through the interplanar gap of nanometer scale. It has a high sensitivity of ΔR/R0=89 per %RH, low hysteresis of 2.5% and is highly suitable for rapid industrial dry-down tracking in 0.1 to 10.0%RH environment.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

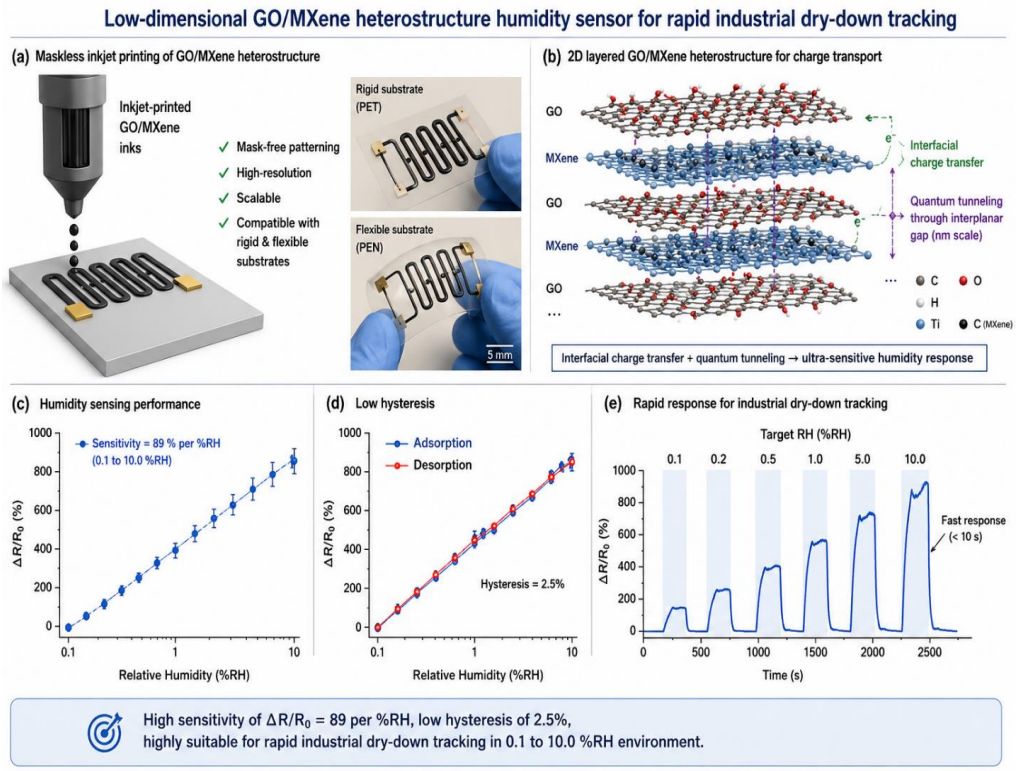

Figure 1: For Rapid Industrial dry-down tracking (Low Dimensional GO/MXene heterostructure humidity sensor.

For absolute mass change measurements rather than direct electrical measurements, mesoporous carbon (FDU-15-COOH) functionalizes with carboxylic groups and drop cast onto Quartz Crystal Microbalance (QCM) resonators. This configuration enables the measurement of sub-parts-per-million tracking (50 to 729 ppmv) by changing the resonant frequency by a known amount (12.4 Hz/ppmv) per ppm of water adsorption. This gravimetric method is the most hysteresis free method (<1.2%), and the carboxyl groups have very reversible hydrogen-bonding sites, which release water molecules quickly during desiccation, this illustration has been given in figure 2.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

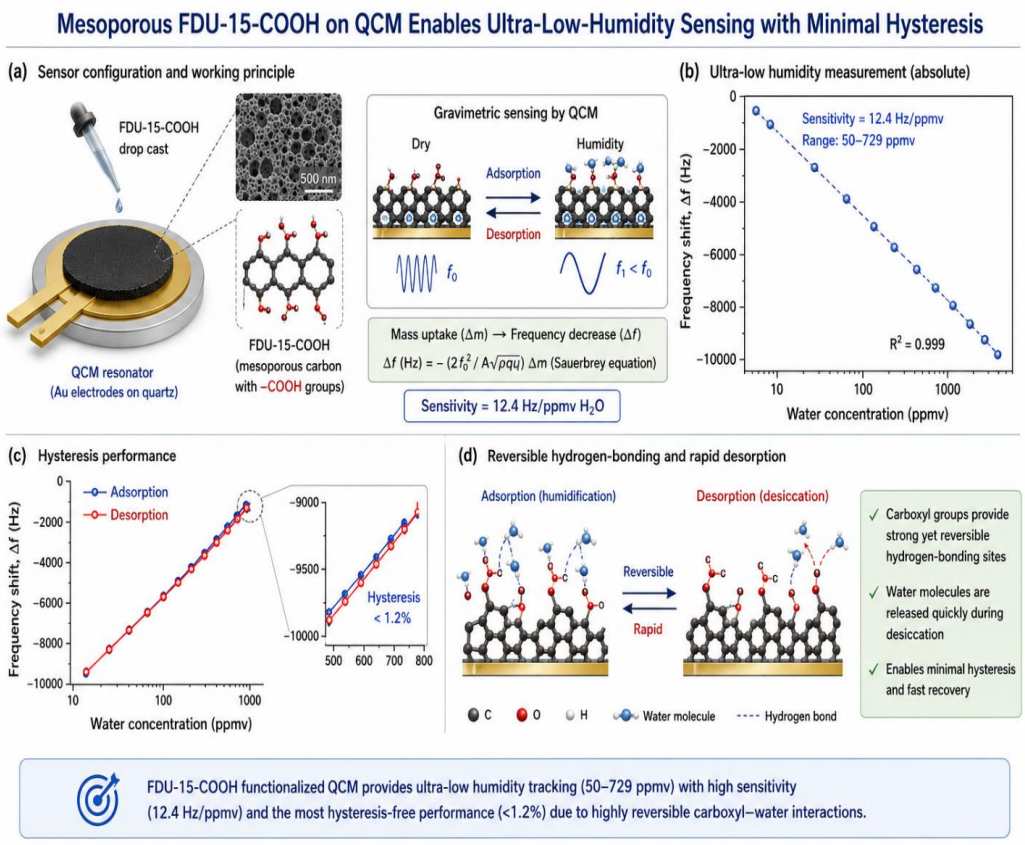

Figure 2: Mesoporous FDU-15-COOH on QCM with Minimal Hysteresis

Finally, it is compared with traditional polymer-based and flexible moisture-sensing bases, which are typically in higher, wider humidity ranges. The composite is prepared by a spin coating and thermal annealing method for use in a different RH range (32.0 to 92.0% RH). It has a huge capacitive sensitivity of 11.0 nF/%RH, exceeding that of any other polymer-carbon composite, and a large hysteresis of $\sim 17.3\%$ because of the highly polarizable polymer-carbon matrix. This delay is due to the fact that water molecules penetrate to a large extent into the swellable chain network of polyvinyl alcohol (PVA) and therefore do not dry out easily.

Likewise, solution spray-casted Nafion polymer blends span a wide 5.0 to 90.0% RH range, have a capacitive sensitivity of 3.2 pF/%RH, and show only a 3.0% RH hysteresis, which are based on structural proton-conducting channels.

Finally, sustainable, vacuum filtering and pressing printing pipeline is used to produce paper based nanopaper sensors that cover a range of 10.0 to 90.0%RH with a flexible resistive sensor at a cost of 10.0 USD. Their electrical resistance change is remarkable, with four orders of magnitude change in resistance, with ionic transport through the cellulose fiber network causing the change, and they have a relatively small hysteresis limit of < 4.0%. These comparisons highlight the requirement for specialized defect-engineered ceramics, MOFs, and 2D heterostructures to realize low hysteresis and high sensitivity in ultra-dry environments, a feat that polymer and cellulose matrices cannot achieve.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

2. The accuracy of a sensor is assessed using; Sensor Evaluation Metrics and Performance Testing.

To accurately evaluate a low-moisture sensor, testing systems that can create "ultra-dry" moisture levels with stable, precise and repeatable moisture levels are necessary. Figure 3 shows the testing of sensor with Dry N_2 and Humid N_2.

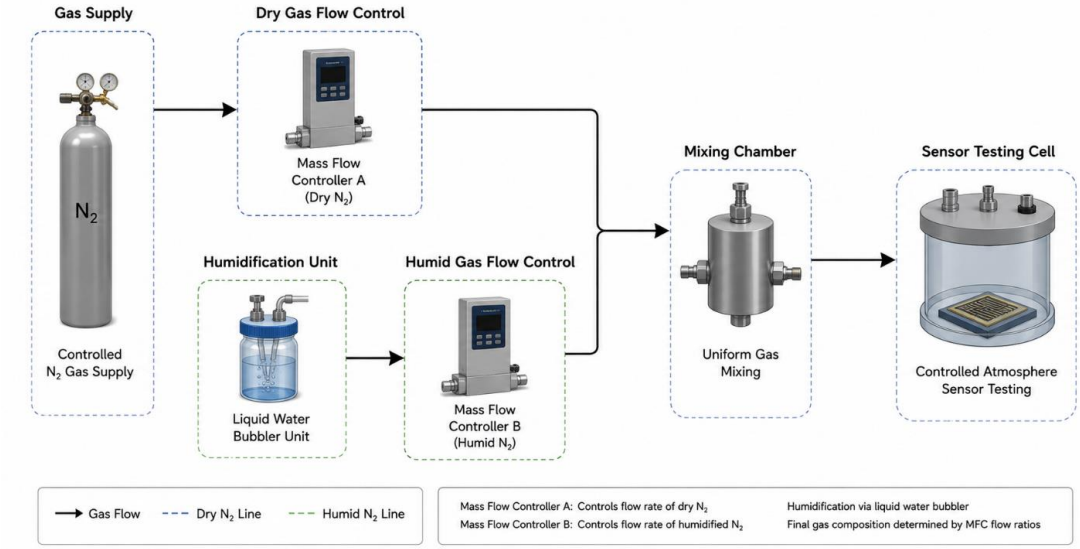

Figure 3: Testing of sensor with Dry N_2 and Humid N_2

2.1 Calibration and Gas-Mixing Systems

Special divided-flow gas systems are required to test sensors below the 10% RH level. Automated mass flow controllers (MFCs) divide high purity dry nitrogen (N2) or argon (Ar) carrier gas into two controlled gas flow paths with an accuracy better than 1 ppm moisture base. One stream goes completely dry and the other goes through a tempered water bubbler to become fully saturated.

Carefully tuning the ratios of these dry and wet streams can precisely create moisture concentrations ranging from trace amounts down to 1 ppmv with repeatability. A primary reference standard, an industrial chilled-mirror hygrometer, is used to check the actual moisture content inside the testing chamber in real-time.

2.2 Key Performance Parameters

2.2.1 Sensitivity

The sensitivity (SC) of capacitive devices is defined as the capacitance change with respect to the change in the relative humidity, pF/% RH:

SC=CRH-CdryΔRH

Resistive devices: Sensitivity is the percentage change in resistance or % or ΔR/R0.

SR=Rdry-RRHRdry×100%

2.2.2 Hysteresis

The difference between the sensor output during humidification (adsorption) and dehumidification (desorption) phase at a specific moisture content is called hysteresis (H):

H=Vads-VdesVFS×100%

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Where Vads and Vdes are the sensor outputs during the adsorption and desorption steps, respectively, and VFS is the full-scale output voltage or signal. Hysteresis is illustrated in figure 4. It is very important that the hysteresis of the sensor is as low as possible, so as to track moisture variations with high accuracy both when increasing moisture and when decreasing moisture.

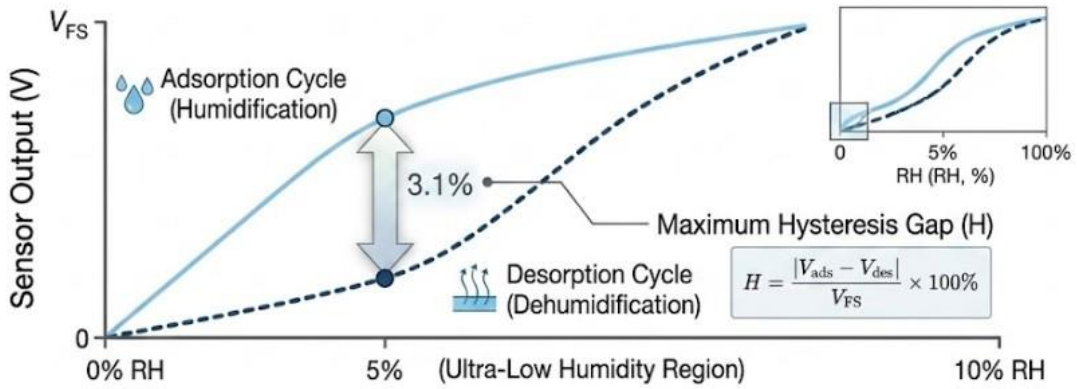

Figure 4: Illustration of hysteresis in humidity sensors

2.2.3 Response and Recovery Times

The Response Time (Tau_{90}) is the time needed for the sensor output to reach 90% of its final steady state value after a moisture concentration step increase.

Recovery Time (t90): The time it takes the sensor output to recover to within 10% of the baseline value after a step decrease in moisture concentration.

Recovery times may be much longer than response times in ultra-dry environments. This time lag would be due to the fact that the activation energy for breaking stronger chemisorption bond of isolated water molecules trapped in the deep structural pores would be higher [1-3].

The stability and drift coefficient for the long-term stability is calculated as follows. The long-term stability drift coefficient is calculated as follows.

Long-term stability is a measure of the sensor's capacity to retain its calibration profile over a long duration of operation. Baseline drift in low moisture systems can occur from irreversible chemical adsorption, or from the permanent poisoning of the active surface sites by trace volatile organic compounds (VOCs). This drift is addressed through a high performance sensor that can be thermally regenerated or doped with materials periodically.

3. Advanced Engineering Trends: AI Integration and Smart Systems.

With the development of industrial automation and the Internet of Things (IoT), the present low moisture sensor is transforming from a basic component into a smart, interdependent system (Loconsole, 2025). Figure 5 shows the IoT framework for capacitive sensors.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

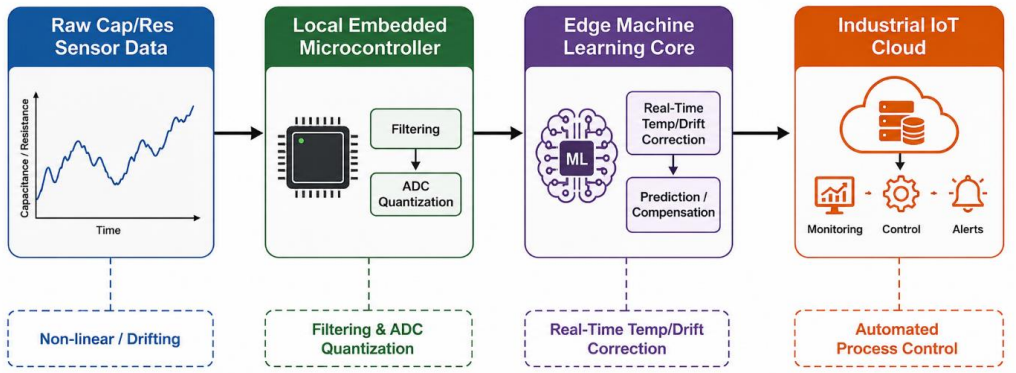

Figure 5: IoT framework for Capacitive Sensors

The (Non-linear/Drifting) section is followed by the (Filtering & ADC Quantization) section and then by the (Real-Time Temp/Drift Correction) section and finally the (Automated Process Control) section.

3.1 Calibration for Machine Learning and Edge-AI

One of the key problems to be tackled with the low moisture sensors is the non-linear response curve and cross-sensitivities of these low moisture sensors to ambient temperature fluctuations. To overcome these limitations, the integration of machine learning models into edge computing microcontrollers can help.

The sensor system can use localized algorithms like Artificial Neural Networks (ANNs), Support Vector Regression (SVR), or multi-variable polynomial calibration matrices, which interpret the raw capacitance/resistance readings along with the real-time data from an adjacent temperature sensor. This automatic correction step is intended to cancel out any thermal drift and linearize the output signal of the sensor directly at the level of the hardware (Alam, 2025; Loconsole, 2025).

3.2 Self-Regenerating Systems

Advanced sensor architectures include integrated micro-heaters, including patterned platinum Pt micro-heating elements on the back of the substrate, to achieve baseline stability due to irreversible chemisorption. If there is a lag in the response or a drift, an automatic control circuit activates a short high-temperature thermal pulse (120 to 180 °C). This localized heating breaks the strongly bound hydroxyl groups on the surface and restores the active sensing surface without affecting the surrounding electronics.

3.3 Distributed IoT Architectures

Low-power wireless communication modules like LoRaWAN, Zigbee, or Bluetooth Low Energy (BLE) are now being integrated directly onto the sensor PCB, making it easier to develop and implement new sensor technologies in the field (Comegna, 2025). These smart sensor nodes will run reliably on battery for up to five years, or on an energy-harvesting module for several years.

These nodes are interconnected in a mesh network in large-scale facilities such as semiconductor clean rooms or chemical manufacturing plants. This will enable real-time spatial monitoring of trace amounts of moisture, which will allow for rapid detection of gas leaks and provide uniformity in environmental control.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

4. Opportunities and challenges: the current situation and future prospects

Although tremendous progress has been made in synthesizing and fabricating materials that can be used for ultra-low moisture sensing, there are a number of continuing trade-offs.

Recovery kinetics can be related to sensitivity, with highly sensitive materials inherently requiring high recovery times during dry down cycles (Alam, 2025).

High humidity spikes or ambient contaminants can saturation (or poisoning) the active sensing layer and cause baseline drift.

2D heterostructures are extremely promising, with metal oxides grown by ALD demonstrating excellent properties, but the high-volume, low-cost production of these materials for commercial use is challenging.

Researchers are working on overcoming these limitations by targeted defect engineering, multi-mode optical-electronic sensing mechanisms and environmentally friendly or biodegradable substrates (Loconsole, 2025; Wang, 2026). The solutions offered by overcoming these manufacturing challenges will open a new chapter for trace moisture detection with greater accuracy for critical industrial and scientific processes.

5. Conclusion

Finally, ultra-low-dimensional defect-engineered ceramics, MOFs and polymers are required to shift from swellable polymers to yield high-accuracy trace moisture detection in ultra-dry environments. These high-tech nanomaterials have the potential to be very sensitive, with minimal hysteresis, but there are some persistent challenges such as being not so quick to recover and also being not so benign in the environment. A strong future direction is the machine learning algorithms used for real-time drift correction, the introduction of micro-heaters for localized thermal self-regeneration, and low-power distributed wireless IoT architectures. Given the manufacturing and recovery challenges these address, the successful resolution of those challenges will open the door to reliable, intelligent spatial monitoring for critical manufacturing processes.

Acknowledgement

This study has been completed in time due to leading efforts from Dr. Ronak Ali, an Assistant Professor at the Benazir Bhutto Shaheed University of Technology and Skill Development Khairpur Mirs.

References

Heiba, Hany Fathy, Jay C. Bullen, Andreas Kafizas, Camille Petit, Sarah Fearn, Stephen J. Skinner, and Dominik J. Weiss. "Engineered Sn-TiO2@ SnO2 and SnO2@ Sn-TiO2 heterophotocatalysts for enhanced As (III) remediation: A comprehensive bulk and surface characterization and precise photocatalytic oxidation rates determination." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 702 (2024): 135087.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Wang, Tingting, and Liang Cheng. "Hollow hierarchical TiO2-SnO2-TiO2 composite nanofibers with increased active-sites and charge transfer for enhanced acetone sensing performance." *Sensors and Actuators B: Chemical* 334 (2021): 129644.

Uddin, Md Tamez. "Metal oxide heterostructures for efficient photocatalysts." PhD diss., Université Sciences et Technologies-Bordeaux I; Technische Universität (Darmstadt, Allemagne), 2013.

Paul, Nibedita, Debarun Dhar Purkayastha, and M. Ghanashyam Krishna. "TiO2/SnO2 and SnO2/TiO2 heterostructures as photocatalysts for degradation of stearic acid and methylene blue under UV irradiation." *Superlattices and Microstructures* 129 (2019): 105-114.

전정훈. "Synthesis of SnO2-based hetero-nanostructure and their applications for environmental monitoring and energy storage." PhD diss., 서울대학교 대학원, 2014.

Lyson-Sypien, Barbara, Anna Kusior, Mieczylaw Rekas, Jan Zukrowski, Marta Gajewska, Katarzyna Michalow-Mauke, Thomas Graule, Marta Radecka, and Katarzyna Zakrzewska. "Nanocrystalline TiO2/SnO2 heterostructures for gas sensing." *Beilstein journal of nanotechnology* 8, no. 1 (2017): 108-122.

Xu, Hongyan, Dianxing Ju, Zhengrun Chen, Rui Han, Ting Zhai, Huanqin Yu, Caiyun Liu, Xiangwen Wu, Jieqiang Wang, and Bingqiang Cao. "A novel hetero-structure sensor based on Au/Mg-doped TiO2/SnO2 nanosheets directly grown on Al2O3 ceramic tubes." *Sensors and Actuators B: Chemical* 273 (2018): 328-335.

Jamil, Mahmood. "Advanced Electrode Materials for Energy Storage: Sn/TiO2 Hybrid Nanocomposite, Zinc Air Battery, and Transition Metal Sulfide Heterostructure Anodes." PhD diss., ResearchSpace@ Auckland, 2025.

Mourão, Henrique AJL, Waldir Avansi Junior, and Caue Ribeiro. "Hydrothermal synthesis of Ti oxide nanostructures and TiO2: SnO2 heterostructures applied to the photodegradation of rhodamine B." *Materials Chemistry and Physics* 135, no. 2-3 (2012): 524-532.

Howayek, Tia Maria, Mahmoud Abid, Haitham Maslouh, Roman Viter, Djamel Bezzerga, Jisang Hong, Amr A. Nada et al. "TiO2/SnO2 photocatalysts by electrospinning and atomic layer deposition for pharmaceutical contaminant removal." *Journal of Science: Advanced Materials and Devices* 10, no. 3 (2025): 100945.

Howayek, Tia Maria, A. B. I. D. Mahmoud, Haitham Maslouh, Igor Iatsunskyi, C. O. Y. Emerson, Loic Assaud, David Cornu, Roland Habchi, and Mikhael Bechelany. "Atomic layer deposition of Pd nanoparticles on TiO2/SnO2 nanofibers for improved visible-light photocatalytic degradation of acetaminophen." *Ceramics International* (2026).

Nie, Anmin, Jiabin Liu, Qianqian Li, Yingchun Cheng, Cezhou Dong, Wu Zhou, Peng Wang et al. "Epitaxial TiO 2/SnO 2 core–shell heterostructure by atomic layer deposition." *Journal of Materials Chemistry* 22, no. 21 (2012): 10665-10671.

Li, Can, Hongyu Xu, Chongyang Zhi, Zhi Wan, and Zhen Li. "TiO2/SnO2 electron

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

transport double layers with ultrathin SnO2 for efficient planar perovskite solar cells." *Chinese Physics B* 31, no. 11 (2022): 118802.

Ng, Siowwoon, Jan Prášek, Raul Zazpe, Zdeněk Pytlíček, Zdenek Spotz, Jhonatan Rodriguez Pereira, Jan Michalička et al. "ALD SnO2 coated anodic 1D TiO2 nanotube layers for low concentration NO2 sensing." *ACS Applied Materials and Interfaces, vol. 12, iss. 29, 22 July 2020* (2020).

Mortelliti, Michael J., Milan Y. Patel, and Jillian L. Dempsey. "Ultrathin Tin-Doped Titanium Oxide by Atomic Layer Deposition on a Mesoporous Substrate: Physical/Electronic Structure, Spectroelectrochemistry, and Interfacial Charge Transfer." *The Journal of Physical Chemistry C* 126, no. 11 (2022): 5265-5282.

Chang, Siliang. "Atomic Layer Deposition of Tin Titanate-Achieving Ferroelectricity And Beyond." PhD diss., University of Illinois Chicago, 2018.

전정훈. "Synthesis of SnO2-based hetero-nanostructure and their applications for environmental monitoring and energy storage." PhD diss., 서울대학교 대학원, 2014.

Assi, Ahmed A., Wasan R. Saleh, and Ezzedin Mohajerani. "Investigate of TiO2 and SnO2 as electron transport layer for perovskite solar cells." In *AIP Conference Proceedings*, vol. 2290, no. 1, p. 050039. AIP Publishing LLC, 2020.

Zheng, Zhi-Wei, Shi-Ying He, Zhan-Yuan Huang, Yi-Wei Wang, Xiao-Fei Zhang, Lang-Xi Ou, David Wei Zhang, Hong-Xiu Yu, and Hong-Liang Lu. "Fabrication of MEMS-based TiO2/SnO2 core-shell nanowires sensor for enhanced H2S sensing." *Ceramics International* 51, no. 20 (2025): 31703-31712.

Kayani, Zohra Nazir, Farhat Saleemi, and Iffat Batool. "Effect of calcination temperature on the properties of ZnO nanoparticles." Applied Physics A 119, no. 2 (2015): 713-720.

Kleitz, Freddy, Wolfgang Schmidt, and Ferdi Schüth. "Evolution of mesoporous materials during the calcination process: structural and chemical behavior." *Microporous and mesoporous materials* 44 (2001): 95-109.

Stanmore, Brian R., and Patrick Gilot. "calcination and carbonation of limestone during thermal cycling for CO2 sequestration." *Fuel processing technology* 86, no. 16 (2005): 1707-1743.

Yu, Jiaguo, Huogen Yu, Bei Cheng, and C. Trapalis. "Effects of calcination temperature on the microstructures and photocatalytic activity of titanate nanotubes." *Journal of Molecular Catalysis A: Chemical* 249, no. 1-2 (2006): 135-142.

Yu, Jiaguo, Huogen Yu, Bei Cheng, and C. Trapalis. "Effects of calcination temperature on the microstructures and photocatalytic activity of titanate nanotubes." *Journal of Molecular Catalysis A: Chemical* 249, no. 1-2 (2006): 135-142.

Rand, B. "Calcination." In *Concise Encyclopedia of Advanced Ceramic Materials*, pp. 49-51. Pergamon, 1991.

Scalera, Francesca, Francesca Gervaso, K. P. Sanosh, Alessandro Sannino, and A. J. C. I. Licciulli. "Influence of the calcination temperature on morphological and

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

mechanical properties of highly porous hydroxyapatite scaffolds." *Ceramics International* 39, no. 5 (2013): 4839-4846.

Chen, Yung-Fang, Chi-Young Lee, Ming-Yu Yeng, and Hsin-Tien Chiu. "The effect of calcination temperature on the crystallinity of TiO2 nanopowders." *Journal of crystal growth* 247, no. 3-4 (2003): 363-370.

Kim, Min Gu, Jeong Min Kang, Ji Eun Lee, Kang Seok Kim, Kwang Ho Kim, Min Cho, and Seung Geol Lee. "Effects of calcination temperature on the phase composition, photocatalytic degradation, and virucidal activities of TiO2 nanoparticles." *ACS omega* 6, no. 16 (2021): 10668-10678.

Sumida, Kenji, Kang Liang, Julien Reboul, Ilich A. Ibarra, Shuhei Furukawa, and Paolo Falcaro. "Sol–gel processing of metal–organic frameworks." Chemistry of Materials 29, no. 7 (2017): 2626-2645.

Uma, Kasimayan, Guan-Ting Pan, and Thomas C-K. Yang. "The preparation of porous sol-gel silica with metal organic framework MIL-101 (Cr) by microwave-assisted hydrothermal method for adsorption chillers." *Materials* 10, no. 6 (2017): 610.

Hunter-Sellars, Elwin, Paola A. Saenz-Cavazos, Anthony R. Houghton, Sean R. McIntyre, Ivan P. Parkin, and Daryl R. Williams. "Sol–gel synthesis of high-density zeolitic imidazolate framework monoliths via ligand assisted methods: exceptional porosity, hydrophobicity, and applications in vapor adsorption." *Advanced Functional Materials* 31, no. 5 (2021): 2008357.

Kong, Jijie, Fengxi Zhu, Wen Huang, Huan He, Jiapeng Hu, Cheng Sun, Qiming Xian, and Shaogui Yang. "Sol–gel based metal-organic framework zeolite imidazolate framework-8 fibers for solid-phase microextraction of nitro polycyclic aromatic hydrocarbons and polycyclic aromatic hydrocarbons in water samples." *Journal of Chromatography a* 1603 (2019): 92-101.

Wychowaniec, Jacek K., Haneesh Saini, Błażej Scheibe, Deepak P. Dubal, Andreas Schneemann, and Kolleboyina Jayaramulu. "Hierarchical porous metal–organic gels and derived materials: from fundamentals to potential applications." *Chemical Society Reviews* 51, no. 21 (2022): 9068-9126.

Poddighe, Matteo, and Plinio Innocenzi. "Hydrophobic thin films from sol–gel processing: A critical review." *Materials* 14, no. 22 (2021): 6799.

Papynov, E. K., M. S. Palamarchuk, V. Yu Mayorov, E. B. Modin, A. S. Portnyagin, T. A. Sokol'nitskaya, A. A. Belov, I. G. Tananaev, and V. A. Avramenko. "Sol-gel (template) synthesis of macroporous Mo-based catalysts for hydrothermal oxidation of radionuclide-organic complexes." *Solid State Sciences* 69 (2017): 31-37.

Jia, Guangwen, Ao Zheng, Xiao Wang, Lu Zhang, Ling Li, Chenxing Li, Yan Zhang, and Lingyan Cao. "Flexible, biocompatible and highly conductive MXene-graphene oxide film for smart actuator and humidity sensor." Sensors and Actuators B: Chemical 346 (2021): 130507.

Zhu, Xiaowen, Xiaoli Liu, Peng Wang, Fei Wu, Shaowen Mu, Jianhong Hao, Xiaomeng Yao et al. "High-Performance Paper-Based Humidity Sensor with Self-Assembling 3D Composite Structure Utilizing MXene-Functionalized

Online ISSN 3007-3197
Print ISSN 3007-3189

Graphene Oxide Strategy for Wearable Medical Monitoring." *Advanced Materials Technologies* 11, no. 4 (2026): e01540.

Seekaew, Yotsarayuth, Supaporn Kamlue, and Chatchawal Wongchoosuk. "Room-temperature ammonia gas sensor based on Ti3C2Tx MXene/graphene oxide/CuO/ZnO nanocomposite." *ACS Applied Nano Materials* 6, no. 10 (2023): 9008-9020.

Ma, Jia-Nan, Yong-Lai Zhang, Yu-Qing Liu, Dong-Dong Han, Jiang-Wei Mao, Jia-Rui Zhang, Wu-Chao Zhao, and Hong-Bo Sun. "Heterogeneous self-healing assembly of MXene and graphene oxide enables producing free-standing and self-reparable soft electronics and robots." *Science Bulletin* 67, no. 5 (2022): 501-511.

Ma, Xinyu, Aiqi Wang, Jinlei Miao, and Tingting Fan. "2D lamellar membrane with MXene hetero-intercalated small sized graphene oxide for harsh environmental wastewater treatment." *Separation and Purification Technology* 311 (2023): 123248.

Xu, Kaizheng, Yingyi Ma, Shun Yao, and Xiaoting Liu. "3D porous rGO/MXene architecture with enhanced and customizable electrochemical performance." *Journal of Materials Science* 58, no. 35 (2023): 13957-13973.