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ARTICLE

Recent advances on MXene based self-powered electrochemical sensors

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Ajith Mohan Arjun^{1*}, Menon Ankitha², Manjusha Mathew³, Sanjiv Sharma^{1*}, P Abdul Rasheed^{4,2*}

Self-powered electrochemical sensors (SPECS) offer a transformative alternative by integrating energy harvesting directly with analyte detection, enabling autonomous operation without external power sources. This review focuses on the merits of employing MXenes in the construction and performance of SPECS by evaluating how MXenes are employed as active components and how it enhance the performance of various SPECS platforms. We broadly classified MXene based SPECS as enzyme biofuel cell-based sensors, microbial and bio photoelectrochemical based sensors, and other SPECS. The key attributes of MXenes including high conductivity, tunable surface chemistry, are ideal for immobilizing active species in the SPECS. The significant capacitance and catalytic potential of MXenes are explored towards enhancing charge transport in SPECS. This enables robust interfaces, facilitating signal amplification, and forming advanced functional composites within these self-powered devices. By utilizing these unique properties of MXenes, the development of highly sensitive, stable, and potentially miniaturized autonomous sensors is becoming increasingly feasible, paving the way for next-generation sensing solutions.

1. Introduction

Electrochemical sensors are essential tools, playing a pivotal role across diverse fields including environmental monitoring, healthcare, food industry, agriculture, safety and security, and biotechnology research. A key operational requirement for conventional electrochemical sensors, despite their widespread utility, is their reliance on external power sources like batteries (for portable devices) or mains electricity (for stationary systems). This fundamental dependency on external power introduces significant limitations concerning device self-sufficiency, overall sustainability, system resilience, maintenance logistics, and environmental impact. Introduced to overcome these challenges, self-powered electrochemical sensors (SPECS) represent a transformative

approach and a significant evolution in sensor technology.^{1, 2} These SPECS operate by generating the electrical energy autonomously. This energy generation occurs through a process where the power output is directly controlled by the presence and concentration of the target analyte.³ This integration of in-situ power generation along with sensing represents a paradigm shift towards more sustainable, autonomous, and simplified sensing platforms, which leads to the development of next-generation devices.

The autonomous generation of power in SPECS directly addresses the significant sustainability challenges posed by conventional sensors. By eliminating the need for external power sources like batteries or solar cells, SPECS drastically reduces the overall material usage involved in sensor construction. This not only conserves resources but also frees up valuable materials, including precious metals and rare earth elements used in batteries, for other critical applications. Furthermore, many SPECS, particularly those based on biofuel cells, utilize biomaterials like enzymes and microbes that are more abundant and less environmentally intensive to produce than the components of traditional power sources⁴. This reduction in the reliance on resource-intensive, non-renewable materials directly results in a smaller carbon footprint and a more sustainable, self-sufficient sensing platform. This shift marks a move toward a circular

¹Department of Pharmacy and Therapeutics, Institute of Systems, Molecular and Integrative Biology, University of Liverpool, 6 W Derby St, Liverpool L7 8TX.

²Department of Chemistry, Indian Institute of Technology Palakkad, Palakkad, Kerala 678 623, India

³Department of Chemistry, Nirmalagiri College, Kuthuparamba, Kannur, Kerala, India-670701

⁴Department of Biological Sciences and Engineering, Indian Institute of Technology Palakkad, Palakkad, Kerala 678 623, India

*arjun.mohan@liverpool.ac.uk (AMA)

*Sanjiv.Sharma@liverpool.ac.uk (SS)

*abdulrasheed@iitpkd.ac.in (PAR)

† Footnotes relating to the title and/or authors should appear here.

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economy model for sensors, where the device's operational power is seamlessly integrated with its sensing function, minimizing waste and environmental impact from cradle to grave.

This paradigm shift towards SPEC systems needs to have innovative device designs that are capable of harvesting energy directly from their surroundings or from the electrochemical sensing reaction happening in the system itself. This can be realized by introducing diverse energy conversion strategies integrated directly within the sensor design. The key approaches include (1) harnessing biomechanical energy by using piezoelectric or triboelectric effects to convert vibrations or pressure changes,⁵ (2) exploiting biochemical reactions similar to enzymatic biofuel cells, where analyte consumption generates current,² (3) utilizing thermal gradients via thermoelectric generators,⁶ (4) capturing ambient light through photovoltaic components,⁷ and (5) converting chemical potential directly into electricity.⁸ The crucial aspects of design, operation, and potential applications of the sensor are entirely dependent on the selection of the energy harvesting mechanism used in the sensor system. For example, a wearable sensor can utilize the body movement via triboelectric nanogenerators, while an environmental sensor can utilize a biofuel cell powered by pollutants.⁹ Hence, the sensor design should focus on analyte detection and efficient power generation units in addition to the integration of sensing elements with miniaturized, and operational demands of the sensor.

There are mainly two different approaches such as biofuel cells (BFCs) and photoelectrochemical (PEC) reactions, generally utilized in self-powered electrochemical sensing systems. These systems align with biological and environmental monitoring needs in a way that they generate power directly from metabolites readily available in physiological fluids (like glucose or lactate) in the case of BFCs, or by converting the light energy in PEC systems. A BFC-based self-powered system involves designing a fuel cell electrode with a primary biocatalyst for power generation, and a bioreceptor element that undergoes bioreceptor-analyte interaction, which influences the rate of the power-generating reaction. This can be either enzymatic biofuel cells (EBFCs), which can generate electrical power through highly specific biochemical reactions catalyzed by enzymes

immobilized on electrode surfaces or microbial fuel cells (MFCs), which utilize the metabolic activity of electrogenic microorganisms to convert the chemical energy stored in organic matter directly into electricity. These EBFCs show high specificity originating from the enzymatic reactions making them attractive for detecting particular biomarkers or metabolites.¹⁰ In MFCs, changes in the MFC's power output can correlate with fluctuations in the concentration of the microbial substrate (e.g., measuring biochemical oxygen demand in wastewater) or the presence of substances that inhibit or stimulate microbial activity (e.g., toxins).¹¹

For sensors leveraging mechanical (piezoelectric or triboelectric) or thermal energy, the operating principle involves the analyte typically controlling a physical energy conversion process indirectly. In contrast, photoelectrochemical (PEC) systems utilize semiconductor materials (photoelectrodes) that absorb light to generate electron-hole pairs; these charge carriers then drive electrochemical reactions, leading to electricity generation.¹² The produced photocurrent or photovoltage will be highly sensitive to the intensity of incident light. Interactions between the target analyte and the photoelectrode surface can alter PEC reactions and this can be used for light-controlled sensing or detection based on analyte-induced changes in the photo-response. Bio-photoelectrochemical cells (BPECs) are a specialized system consisting of both bioelectrocatalytic and photoelectrocatalytic components for converting light and chemical energy into electricity simultaneously.¹³ In addition, BPECs hold the advantages of biocompatibility from EBFCs and robustness from PECs.¹⁴

In both BFC and PEC-based SPECS, the analyte interaction is linked to the core energy generation mechanism and the sensing information can be extracted by monitoring the output power of the devices with relatively simple instrumentation. Hence, the processes at the transducer stage can be designed to integrate both the power production and sensing elements closely together to simplify the manufacturing process. Fig. 1 shows the illustration of enzymatic biofuel cells (EBFCs), microbial fuel cells (MFCs) and bio-photoelectrochemical fuel cells (BPFCs).



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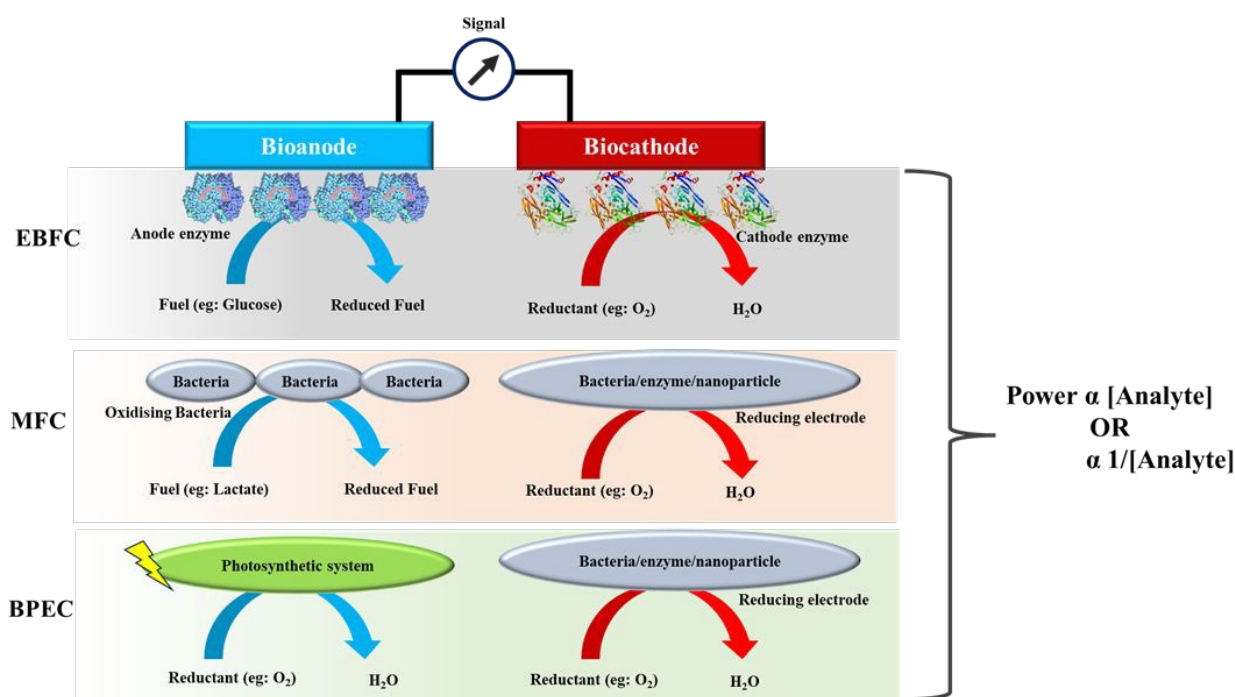


Fig. 1. Illustration of enzymatic biofuel cells (EBFCs), microbial fuel cells (MFCs) and bio-Photoelectrochemical fuel cells (BPECs). These systems utilize biological components (enzymes, microbes) and photosynthetic systems to catalyze redox reactions at the anode/bioanode and cathode/biocathode, generating an electrical signal (power) which is typically proportional or inversely proportional to the concentration of a target analyte. The authors have drawn this image.

For the successful realization of BFC and PEC-based SPECS, it is highly essential to consider the use of advanced materials with the capability for rapid electron transfer towards the sensor signal readout. In addition, these advanced materials can support both energy conversion and sensing processes through analyte recognition/interaction mechanism. Various traditional materials like noble metals¹⁵, carbon nanotubes¹⁶, graphene¹⁷, and conducting polymers¹⁸ have been explored for achieving optimal synergy between power generation, sensing performance. However, the stability, and biocompatibility of these materials remains a significant challenge and this introduce the necessity of novel materials with unique attributes¹⁹.

Among the emerging candidates, MXenes; a new family of two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides with unique properties have gathered substantial interest for electrochemical applications including self-powered sensing applications.²⁰ MXenes are synthesized from their precursor MAX phases via selective etching with hydrofluoric acid or alternative etchants. MXenes possess a characteristic combination of unique properties that make them exceptional candidates for developing integrated sensing and power generation platforms.²¹ MXenes are represented by the general formula $M_{n+1}X_nT_x$ (where M is an early transition metal like Ti, V, Mo, etc.; X is C or N; $n=1-4$; and T_x denotes surface functional groups like -F, -O, and -OH).²² They also



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exhibit excellent metallic conductivity, which ensures efficient charge transport comparable to or exceeding other traditional electrode materials for electrochemical applications in terms of minimizing internal resistance, and maximizing power output.²³ Also, the field of MXenes has been moving towards employing more environmentally friendly chemicals and methods for their synthesis. The application of diluted fluoride based etchants²⁴, electrochemical etching²⁵, vapour deposition based synthetic techniques²⁶, and use of waste streams as precursors will help towards making the MXene a sustainable option²⁷.

Additionally, the surface functionalization of MXenes rendering them hydrophilic and providing numerous anchor points for immobilizing enzymes, aptamers, antibodies, or other biorecognition elements which are essential for highly selective sensing in BFCs.²⁸ Furthermore, the high specific surface area possessed by these materials enables high catalyst loading, thus enhancing the interaction with the surrounding medium (e.g., electrolyte or biological fluid). Some MXenes also exhibit intrinsic electrocatalytic or co-catalytic activity that can be used to replace other expensive catalysts or enhance efficiency in photoelectrochemical systems.²⁹ The tunable surface chemistry along with possibility of diverse elemental compositions and their ability to form advanced hybrid nanocomposites with other materials opens new avenues for modifying their electrocatalytic activity towards specific reactions for energy generation involved in BFC (like oxygen reduction or fuel oxidation) or in PEC.³⁰ The tunable surface chemistry, and also presence of hydrophilic groups on MXenes also result in these materials being friendly for large scale manufacturing due to these materials being able to be formulated into inks. Formulations of MXenes with biomaterials like enzymes, microbes, and photosynthetic organelles offer attractive opportunities for manufacturing of SPECS^{31, 32}.

Xu et al. employed density functional theory (DFT) to unravel the interfacial electronic structure and energetics of MXene/transition-metal oxide (TMO) heterostructures, using -OH, -O-, -F, and mixed-terminated $Ti_{n+1}C_nT_x$ MXenes coupled with anatase TiO_2 ³³. Their results reveal that the magnitude of interfacial charge transfer is highly dependent on MXene surface chemistry. Among the various terminations, OH-functionalized MXenes exhibited the largest work-function disparity (~ 1.6 eV for MXene versus 6.4 eV for TiO_2), driving substantial electron migration (~ 0.9 e nm⁻²) from the MXene layer into the TiO_2 interface. This strong charge redistribution not only

lowers the interfacial electronic barrier but also enhances adhesion through hydrogen bonding, thereby establishing an electronically coupled and structurally robust junction. Conversely, -O- or F-terminated MXenes exhibited minimal charge transfer and weaker interfacial binding, underscoring the critical role of surface terminations in governing interfacial electronic communication.

While MXene - TMO heterostructures primarily leverage interfacial electron transfer through strong work-function disparities and surface chemistry-driven adhesion, MXene/N-doped graphene hybrids offer a complementary pathway to enhance interfacial kinetics by integrating a highly conductive 2D carbon framework. MXene/N-doped graphene heterostructures exhibit remarkable electrocatalytic efficiency arising from their strong interfacial coupling and accelerated charge-transfer pathways. Density functional theory (DFT) calculations reveal that the metallic conductivity of MXenes, combined with the defect-rich, heteroatom-doped graphene network, establishes a seamless electronic interface that minimizes contact resistance and enhances interfacial electron mobility. Nitrogen dopants in graphene introduce localized electronic states near the Fermi level, which act as additional charge reservoirs and facilitate efficient electron tunneling across the heterojunction. Charge density difference maps further confirm pronounced interfacial electron redistribution, indicating strong electronic coupling between MXene and N-doped graphene. This interfacial polarization not only aligns the energy levels between the two components but also optimizes the adsorption energetics of electroactive species, thereby reducing the kinetic barriers for redox reactions. Collectively, these DFT-derived insights highlight how the synergistic interplay of electronic coupling, defect engineering, and interfacial charge polarization in MXene/N-doped graphene heterostructures provides a robust platform for fast electron-transfer kinetics and stable performance in self-powered electrochemical sensors³⁴.

In addition, MXene-polymer interfaces provide another promising strategy to improve charge-transfer efficiency and interfacial kinetics in SPECS. DFT calculations on $Ti_3C_2T_x$ MXene coupled with polyaniline (PANI) demonstrate pronounced interfacial charge redistribution, with electrons transferring from PANI to MXene due to favorable Fermi-level alignment. This electron transfer generates an intrinsic interfacial electric field, which facilitates directional charge flow and significantly reduces charge-transfer resistance. Partial density of states (PDOS) analysis further reveals the formation of hybridized



electronic states at the interface, which act as efficient charge-transport channels. Additionally, this interfacial coupling enhances the adsorption energetics of electroactive species, thereby accelerating redox kinetics crucial for self-powered signal transduction. Looking forward, the rational design of MXene–polymer interfaces, guided by DFT-driven insights, will be critical to overcoming persistent challenges such as interfacial instability, energy loss, and limited operational lifetime, thereby enabling the next generation of highly efficient, durable, and autonomous SPECS platforms³⁵.

These inherent advantages of MXenes, which can overcome the limitations of conventional materials in terms of sensitivity, stability, and miniaturization can be utilized in developing powerful building blocks for next-generation, high-performance SPECSs. Indeed, many conventional materials struggle with insufficient signal response to low analyte concentrations (sensitivity), tend to degrade or lose accuracy over extended use or in harsh conditions (stability), and present considerable fabrication challenges for creating compact, portable devices (miniaturization). The following sections in the review explore how these unique properties of MXenes are utilized in the design and fabrication of MXene-based SPECS. To provide a clear understanding, the review will discuss specifically systems where MXenes serve as active components, including a detailed comparison of key performance characteristics—such as sensitivity, stability, and operational range—when integrated into EBFC-based, MFC-based, and BPEC-based sensors.

2. MXenes in Enzyme biofuel cell (EBFCs) based self-powered sensors

The use of enzymes in EBFCs entails some drawbacks like the stability of enzymes, issues with proper immobilization resulting in lesser power production. To overcome these limitations, Ji *et al.* introduced an innovative biofuel cell based self-powered sensor design for the detection of lead ion.³⁶ They utilized two-dimensional lamellar gold nanoparticles- $\text{Ti}_3\text{C}_2\text{T}_x$ (AuNPs- $\text{Ti}_3\text{C}_2\text{T}_x$) heterostructures for the anode, in which the AuNPs provided glucose oxidase-like catalytic activity and this can be used to replace the potentially unstable enzymes. In addition, the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene provides signal amplification owing to their excellent charge storage capacity which can solve the potential issues of low current production. In the sensor design, they

used doped carbon-based nanosheets as the cathode with promising oxygen reduction reaction catalytic activity. Together with these anode and cathode modifications, the developed enzyme-free biofuel cell was able to detect lead ion in the range of 0.01–7500 nM with a limit of detection (LOD) of 0.43 pM along with realization of practical applications using human plasma samples.

Even though, SPECS show great potential but are often limited in practical applications due to low energy conversion efficiency and limited selectivity especially in complex samples. As an approach to mitigate these limitations, Sun *et al.* reported a novel self-powered biosensor employing EBFC specifically for ultrasensitive CD44 detection.³⁷ CD44 is a cell-surface molecule involved in many cellular processes and act as a key biomarker and therapeutic target, especially in cancer metastasis. Hence, the sensitive and specific detection of CD44 is highly essential for diagnostic applications which requires advanced sensor platforms. They have synthesized MXene-AuNP composite as shown in Fig. 2(a). The developed biosensor consists of Au-MXene modified bioanode conjugated with glucose oxidase (GOD) and aptamer; and bilirubin oxidase (BOD) conjugated on Au-MXene modified biocathode as shown in Fig. 2(b). Initially, the aptamer with high insulation on the bioanode hindered the electron transfer and produced low open circuit voltage (OCV). When the target CD44 protein was captured by the aptamer at bioanode, it produces structural change at the electrode surface which leads the transfer of electrons and increased the OCV in proportion to the analyte concentration. This clever sensor design achieves promising LOD of 0.052 ng mL^{-1} , excellent selectivity and stability, proving effective in real blood samples without special pre-treatment and highlighting its potential for early cancer diagnosis.



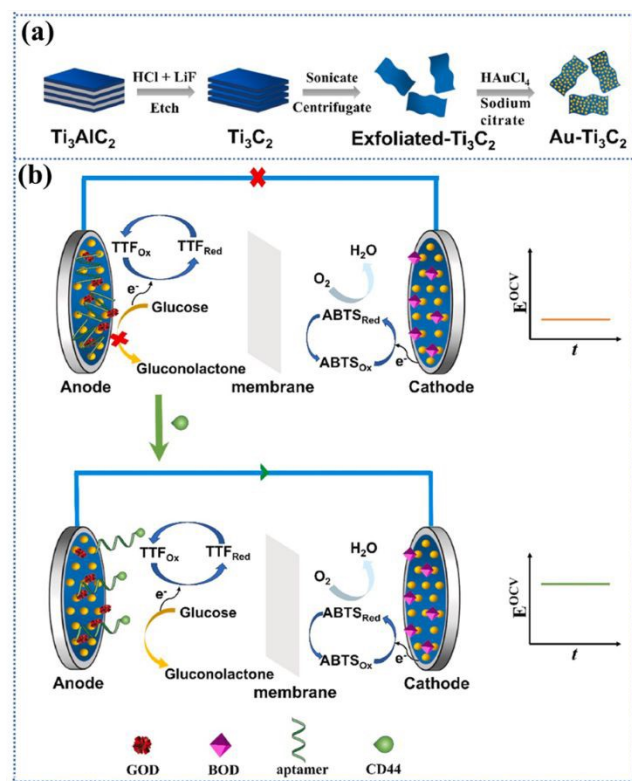


Fig. 2(a). Schematics showing the synthesis of Au-MXene composite (b) the schematic illustration of fabrication of the EBFC self-powered sensor with bioanode and biocathode followed by changes in the OCV upon binding with CD44 protein and the immobilized aptamer. Reproduced with permission from ref.³⁷ Copyright © 2024 Elsevier B.V.

Ji *et al.* developed a novel enzyme-free intra-capacitive biofuel cell (ICBFC) based self-powered sensor for the electrochemical detection of endocrine-disrupting phthalates like di(2-ethylhexyl) phthalate (DEHP).³⁸ The sensor design included the integration of ternary heterostructure capacitive anode and a sensing-interface cathode within a single chamber. The anode is made of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, ultra-small AuNPs, and polypyrrole (PPy) NPs in which AuNPs enables efficient enzyme-free glucose oxidation while the synergistic combination of MXene's double-layer capacitance and pseudo capacitance of the PPy enhances the charge storage. This sophisticated ICBFC based self-powered sensor demonstrated promising LOD of 9.51 pg.L^{-1} for DEHP over a wide linear range, highlighting its potential for rapid, on-site environmental monitoring and public health protection.

In another recent work, Xiao *et al.* reported a flexible, self-powered biosensor for lactate detection based on carbon cloth electrodes

immobilized with lactate oxidase (LOD) and bilirubin oxidase (BOD) on reduced graphene oxide (rGO).³⁹ Here, MXene was incorporated into a polypyrrole/polyurethane hydrogel and used as substrate for sensor assembly for placing the electrodes. This integration of MXene hydrogel enhanced the current output by 15-fold due to improved electron mobility and ionic conductivity of MXenes. The developed sensor produced a maximum power density of $\sim 3 \mu\text{W.cm}^{-2}$ at 100 mM lactate and showed a linear current response in the physiological window of lactate. This can be used as a biocompatible and scalable route for future wearable applications enabling accurate, continuous, and self-powered sensing of lactate in physiological environments.

3. MXenes in bio photoelectrochemical (BPEC) based self-powered electrochemical sensors

Self-powered photocatalytic fuel cell-based sensors by integrating bio element recognition with fuel concentration-dependent output power can be used for electrochemical analysis. The problems with existing self-powered photocatalytic fuel cell-based sensors are poor energy conversion efficiency and unsuitable for routine use. To address these problems, Qui *et al.* designed a multi-functional self-powered photocatalytic fuel cell platform for the detection of ochratoxin A, which is a toxic and potentially carcinogenic mycotoxin produced by certain molds.⁴⁰ Here, the photoanode of the sensor was constructed with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene- TiO_2 composite and the cathode was modified with Prussian blue (PB), enabling a visual checking capability through color change along with electrical signal. For realizing the sensing mechanism, mesoporous silica nanoparticles (MSNs) were used as nanocontainers loaded with glucose, and aptamers specific to ochratoxin A. The schematics of the sensor fabrication and how the bioresponsive controllable glucose release helps in the detection of Ochratoxin A is given in Fig. 3. When, the analyte reacts with aptamer, the glucose is released from mesoporous silica nanoparticles which powers the photocatalytic fuel cell. The released glucose was photo-oxidized by $\text{Ti}_3\text{C}_2\text{T}_x$ MXene- TiO_2 composite under visible light illumination and the produced electron can reduce PB which results a high output power of $23.516 \mu\text{W cm}^{-2}$ and the developed sensor showed promising analytical performance towards ochratoxin A in the range of 0.2 ppb–20 ppb with a LOD of 0.0587 ppb.



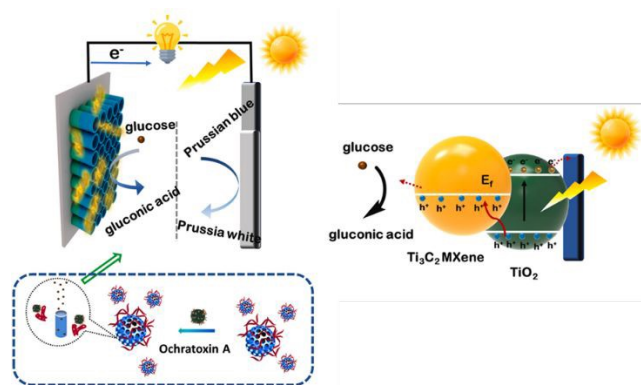


Fig. 3. Schematic illustration of the mechanism of self-powered photocatalytic fuel cell (PFC) based sensors using $\text{Ti}_3\text{C}_2\text{T}_x$ MXene- TiO_2 composite as photoanode and Prussian blue (PB) as cathode for the detection of Ochratoxin A. Reprinted with permission from ref.⁴⁰ Copyright © 2023 Published by Elsevier B.V.

In another work, Jin *et al.* reported a novel self-powered biosensor by uniquely integrating a photocatalytic fuel cell with a molecular imprinting polymer (MIP) for the detection of aflatoxin B1, which is a highly potent carcinogenic mycotoxin.⁴¹ Here, the issue of energy conversion efficiency is tackled by using a MoS_2 - $\text{Ti}_3\text{C}_2\text{T}_x$ MXene heterojunction on indium tin oxide (ITO) as a photoanode within the photocatalytic fuel cell which can harness light energy more effectively. The cathode was made by combination of hemin and graphene to catalyze the reduction of hydrogen peroxide as shown in Figure 4. Simultaneously, the selectivity issue is directly addressed by incorporating the MIP, which is designed to specifically capture the target analyte Aflatoxin B1 (AFB_1) even in presence of interfering agents. In the absence of AFB_1 , the photogenerated holes of photoanodes could promote the oxidation of ascorbic acid (AA) and produces an OCV. When AFB_1 binds to the cavities of MIP, it affects the OCV of the system and this change can be used for the specific and sensitive detection of AFB_1 with a LOD of 0.73 pg mL^{-1} as illustrated in Figure 5. The developed sensor uses this dual approach of MIP for specific target recognition and MXene for efficient light-driven signal conversion for photocatalytic fuel cell.

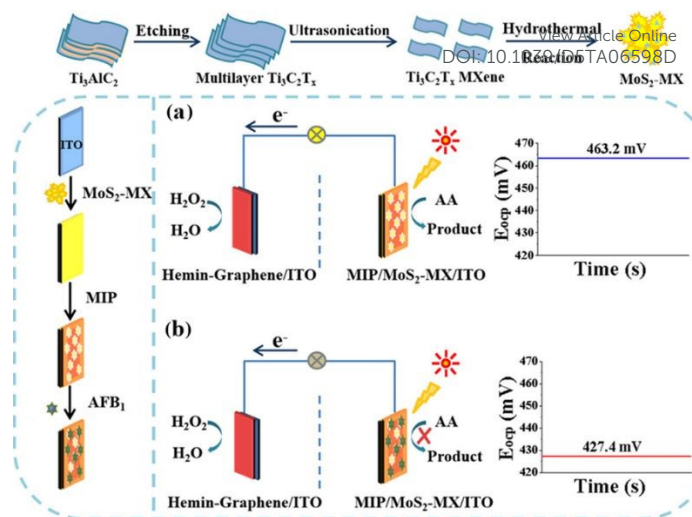


Fig. 4. Schematics showing the self-powered photocatalytic fuel cell-based biosensor for AFB_1 Detection. The synthesis of MoS_2 - $\text{Ti}_3\text{C}_2\text{T}_x$ MXene heterojunction and the fabrication of photoanode is given. (a) The conversion of AA into products in absence of AFB_1 produces an OCV and (b) the OCV reduces in presence of AFB_1 as the conversion of AA is blocked. Reprinted with permission from ref.⁴¹ Copyright © 2021, American Chemical Society.

Ultrasensitive detection of potent toxins like microcystin-RR (MC-RR) is highly critical for environmental safety evaluation and need to fabricate advanced portable and real time sensors with efficient signal amplification for sensitive detection. Towards this aspect, Sun *et al.* constructed photo-driven self-powered BPECs aptasensor for MC-RR using $\text{Ti}_3\text{C}_2\text{T}_x/\text{ZnIn}_2\text{S}_4$ heterojunction as the photoanode and Cu_2O as the photocathode.⁴² The $\text{Ti}_3\text{C}_2\text{T}_x$ MXene in the system enhances charge separation in addition to provide large surface area for immobilization of MC-RR specific aptamer. When MC-RR binds to the aptamer, it causes 'signal-off' mechanism due to steric hindrance, which reduces the photocurrent. In addition, they integrated a matching capacitor, boosting the sensitivity 22-fold, and proposed a USB-sized micro-workstation for capturing instantaneous signals for making the system portable. Under the optimal conditions, this multi-amplification system achieved the photocurrent in linear relation with the concentration of MC-RR with an extremely low LOD of 0.033 pM and demonstrated the practical applicability of the system in fish samples.

In a different approach, a novel dual-power-peak photofuel cell (PFC) based self-powered sensor has been developed for the



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detection of chloramphenicol by introducing dual peak output signals for enhancing the detection accuracy.⁴³ They have utilized persulfate as an initiator for getting dual peak response in the PFC system, which can enhance charge separation and generate a second power peak in the output signal. The photoanode was made of fluorine-doped tin oxide (FTO) modified with BiVO_4 and V_2C MXene followed by modification with aptamer as seen in Fig. 5(a). The incorporation of V_2C MXene accelerated electron transfer, boosting photoelectric conversion efficiency, while an aptamer provides specific recognition of chloramphenicol. The FTO modified with molybdate hexacyanoferrate (MoHCF) as used as photocathode as shown in Fig. 5(b). The construction of the dual-power-peak photocatalytic fuel cell based self-powered sensor is given in Fig. 5(c). When chloramphenicol binds to the aptamer on the photoanode, the output signal of the sensor including two power-peaks which are changed linearly with the concentrations of chloramphenicol (Fig. 5(d)). The quantification of chloramphenicol based on these dual power peaks allowed sensitive detection with LOD of 0.17 pM over a linear range of 0.5 pM to 3 nM, demonstrating a promising strategy for developing highly sensitive and specific multi-signal self-powered sensors.

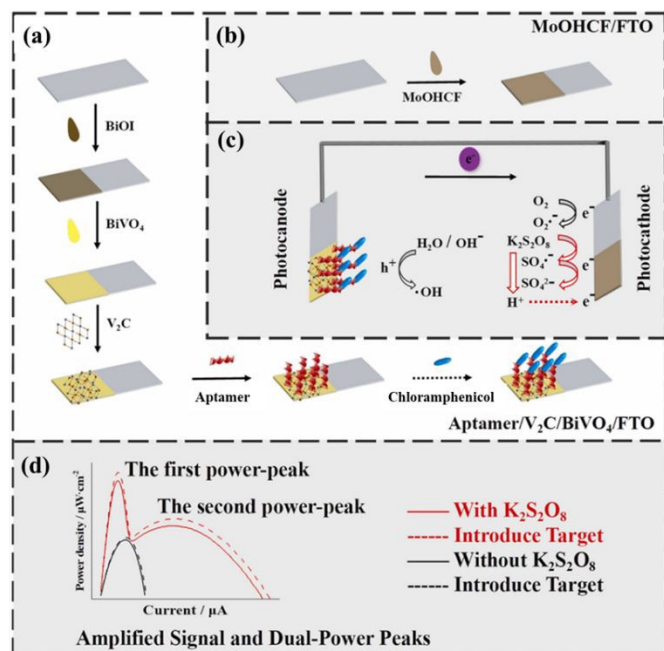


Fig. 5. The schematic showing the fabrication of the dual-power-peak photofuel cell (PFC) based self-powered sensor for the detection of chloramphenicol. (a) fabrication of photoanode. (b) Fabrication of the photocathode. (c) Construction of the dual-power-

peak PFC combining the photoanode and photocathode. (d) Schematic illustration showing the dual-power-peak detection configuration in presence of $\text{K}_2\text{S}_2\text{O}_8$. Reprinted with permission from ref.⁴³ Copyright © 2023 Elsevier B.V. All rights reserved.

4. MXenes in other self-powered electrochemical sensors

Recently, the zinc-air battery (ZAB)-driven self-powered biosensors has shown great potential in the detection of trace analytes, demonstrating high output potential and excellent stability and sensitivity.⁴⁴ Most ZABs can generate the high output voltage and energy density and can be used in biosensing applications. The major concern in the fabrication of superior ZAB-assisted PFC biosensors is to develop an efficient photocatalyst with high photocatalytic ability, fast electron transfer and high bio affinity towards bio probes.⁴⁵ In this context, MXenes are considered as the promising candidate in comparison with other 2D materials considering high electrical conductivity, hydrophilicity and easy surface functionalization.⁴⁶ Various other self-powered sensors have been developed by using MXene as their one of the components. In this aspect, Liu et al. developed a novel dual-modal zinc-air battery (ZAB) driven self-powered electrochemical aptasensor based on heterojunction of V_2CT_x MXene and bimetallic CoNi-layered double hydroxide (CoNi-MLDH) for the detection of cortisol.⁴⁶ They utilized V_2CT_x nanosheets as scaffolds for the *in situ* growth and subsequent formation of CoNi-MLDH nanosheets. The V_2CT_x MXene in CoNi-MLDH composite enhances the electrochemical activity while the CoNi-LDH enhances the surface area, functionality, oxygen reduction activity, and aptamer affinity of the composite. By utilizing these advantages, the developed ZAB driven self-powered aptasensor was able to achieve a very low LOD of 0.17 fg mL^{-1} , for cortisol.

In another work, a similar ZAB based self-powered aptasensor was proposed by Liu *et al.* for the detection of penicillin G by using Zn plate photoanode and heterojunction made of cadmium-doped MoS_2 nanosheets grown on $\text{Ti}_3\text{C}_2\text{T}_x$ MXene ($\text{Cd-MoS}_2@/\text{Ti}_3\text{C}_2\text{T}_x$) as photocathode.⁴⁷ Fig. 6 shows the schematics of the fabrication of photo-assisted ZAB-driven self-powered aptasensor and detection process by binding the aptamer with penicillin G. The enhanced light absorption, high photoelectric conversion efficiency, and more catalytic active sites of this heterojunction boost the ZAB output voltage to 1.43 V under UV-vis light irradiation. The resulting self-



powered aptasensor displayed an ultralow LOD of 0.06 fg mL^{-1} for penicillin G, with promising specificity and stability, offering a

promising portable sensor for the detection of antibiotics.

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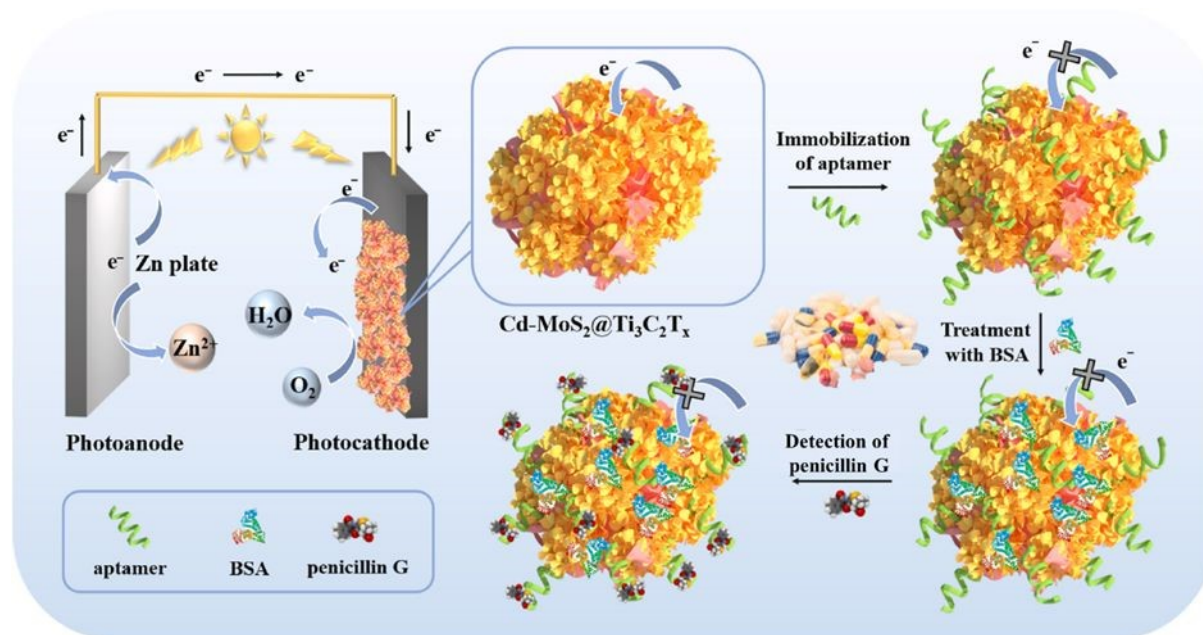


Figure 6. Schematic diagram showing the fabrication steps for the photo-assisted ZAB-driven self-powered aptasensor for the detection of penicillin G and the mechanism of the detection of penicillin G. Reprinted with permission from ref.⁴⁷ Copyright © 2023 Elsevier B.V.

5. Critical Bottlenecks in Self-Powered Electrochemical Sensors (SPECS): Views from MXene and Broader Platforms

Self-powered electrochemical sensors encounter notable energy-related limitations due to the characteristics of their energy harvesters, namely triboelectric nanogenerators. These devices are adept at generating high voltages, but their output currents are often quite modest. This disparity can restrict sensor effectiveness, especially for applications that need robust electrochemical activity or fast responses. Attempts to boost energy output through microstructuring surfaces provide some improvements, but they also introduce challenges related to material degradation and loss of performance stability over time. Issues like fatigue or detachment at electrodes and interfaces can further undermine the reliability of the sensor, underscoring the necessity for wear-resistant materials and stable surface engineering.

The path to functional integration of energy harvesters with sensing circuits is also complicated by the variable and pulsed nature of the generated electrical signals. These fluctuations can make accurate signal measurement difficult and may lead to unwanted phenomena

at the electrode, such as the build-up of polarization or secondary chemical reactions that are not part of the intended sensing process. When several energy harvesting elements are combined, phase mismatches can occur, leading to irregular signal shapes and increased risk of sensor aging due to surface passivation. While using alternating current regimes can sometimes help mitigate these effects, it adds to the complexity of sensor design and the need for precise electrical matching. These SPECS inherently face the challenge of limited energy conversion efficiency due to constrained power harvesting, inefficient interfacial coupling, and low signal transduction rates⁴⁸

Another central challenge lies in the properties and robustness of the electrode materials themselves. While MXene electrodes offer high electrical conductivity and rich surface terminations, practical issues such as restacking of nanosheets and agglomeration significantly reduce accessible surface area and block redox-active sites, resulting in lower energy output and diminished sensor sensitivity. Even beyond MXenes, non MXene materials like carbon nanotubes and metal oxides also hit similar efficiency barriers such as poor wettability, sluggish electron-ion transport, and weak electrode-



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solution coupling hamper comprehensive energy-to-signal conversion in autonomous sensing configurations⁴⁹.

In addition to efficiency, operational instability poses a critical limitation to SPECS lifespan particularly in wearable or biological environments. MXene materials are prone to oxidation, especially under exposure to humidity or oxidative conditions, leading to conductivity degradation and signal drift over time. Biological deployment further introduces biofouling, molecular adsorption, and environmental interference, all of which can obstruct electrode surfaces and disrupt consistent sensing performance. Similarly, non MXene systems such as conductive polymers or metal oxide sensors face structural deformation, polymer degradation, or loss of receptor function limitations that shorten device lifetimes and affect repeatability⁵⁰.

Finally, scalability, reproducibility, and sensor specificity remain formidable obstacles to commercialization. MXene fabrication often depends on harsh etching techniques leading to variability in surface termination (–O, –OH, –F), flake size, and defect density—factors that directly affect electrochemical performance and batch-to-batch consistency. On the non MXene side, heterogeneous hybrids of organic and inorganic elements often struggle with inconsistent receptor attachment, limited analyte specificity, and low selectivity, reducing accuracy in real-world deployments. Addressing these challenges will require green, standardized manufacturing processes, robust surface chemistries, and integrated receptor design to ensure reproducible, selective, and commercially viable SPECS platform.^{48, 51}

In sum, advancing self-powered electrochemical sensors to practical, widespread use will demand solutions that improve both energy harvesting and material stability, while also enabling reliable mass production. Progress toward more sustainable production, better integrated circuit management, and the development of robust, durable interfaces will be key steps. Only by tackling these challenges in concert will the promise of self-powered sensing technologies be fully realized.

A solid foundation for the advancement of self-powered electrochemical sensors has been laid by several key research efforts. Wang and coworkers were pioneers in the field, establishing the concept of wearable self-powered sensors and on-body power grids^{52, 53}. This work created a crucial framework for integrating energy harvesting with sensing technology. Building on this, Yin et al. demonstrated the use of passive perspiration-based biofuel cells, a

concept that can be realized with great efficiency using MXenes due to their high conductivity, hydrophilicity, and ability to preserve the function of power-generating biocomponents⁵⁴. This work provides a clear roadmap for harnessing the unique properties of MXenes in a practical application. Furthermore, a critical question regarding the biocompatibility of MXenes for wearable applications was addressed by Wei Gao and coworkers, who successfully developed a MXene-based platform for monitoring female hormones, thereby proving its viability for direct human use⁵⁵.

Based on the provided data, a direct quantitative comparison between MXene-based SPECS and conventional materials is challenging due to the early stage of MXene research and diverse device architectures. However, qualitative contrasts can be made. MXene-based devices often demonstrate comparable or superior sensitivity and fast response times for specific analytes, as shown by the pM-level detection limits for lead ions and the dynamic ranges for other proteins. For instance, the Au-MXene device for CD44 protein shows versatility with its wide dynamic range. Additionally, MXenes show promising stability with a 98.49% signal retention after 15 days for a cortisol sensor³⁷. This is a significant finding as stability is often a major challenge for nanomaterial-based devices (Table 1). Table 1 shows a comparative analysis of self-powered electrochemical sensors (SPECS) based on MXenes with other nanomaterials. An analysis of Table 1 indicates that MXene- and non-MXene-based SPECS exhibit similar stability and performance metrics. In addition, MXene based modifications are expected to possess better aqueous solution processibility than their pristine carbon counter parts, which makes them more environmentally sustainable for use in SPECS. However, the heterogeneity in reported electrode construction—specifically the varying methodologies, protocols, and modification layers—precludes a comparison of the true stability performance across these reports. A proposed benchmark for MXene-based SPECS is the attainment of higher stability metrics using smaller form factors.

The current lab-scale, beaker-based nature of these devices suggests a low Technology Readiness Level (TRL), likely TRL 1 to TRL 4. This means the primary focus is on establishing fundamental principles and feasibility in a controlled environment. Real-world performance under various environmental conditions like humidity and temperature is typically assessed at higher TRLs (e.g., TRL 5 and 6). Therefore, further research is necessary to move these technologies from the lab to a fabricated device that can be systematically tested



under real-world conditions to address the reviewer's concern and evaluate its resilience to environmental stressors.

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Table 1. Comparative Analysis of Self-Powered Electrochemical Sensors (SPECS): MXenes vs. Other Nanomaterials

Anode	Cathode	Analyte	LOD	Dynamic Range	Construction and performance metrics ($P_{\max}/E_{\text{OCV}}$) at baseline	Stability	Ref
Two-dimensional lamellar gold nanoparticles- $\text{Ti}_3\text{C}_2\text{T}_x$ ($\text{AuNPs-Ti}_3\text{C}_2\text{T}_x$) heterostructures	Doped carbon-based nanosheets	Lead ion (Pb^{2+})	0.43 pM	0.01–7500 nM	Beaker based E_{OCV} : 367 mV	~92% of initial level after 45 days	36
MXene-AuNP composite modified with glucose oxidase (GOD) and aptamer	Au-MXene modified with bilirubin oxidase (BOD)	CD44 protein	0.052 ng/mL	0.5–1000 ng/mL	Beaker based $P_{\max}$: ~1 $\mu\text{W}/\text{cm}^2$ E_{OCV} : 390 mV	~97% after 15 days	37
$\text{Ti}_3\text{C}_2\text{T}_x$ MXene, ultra-small AuNPs, and polypyrrole (PPy) NPs (Ternary heterostructure capacitive anode)	A sensing-interface cathode within a single chamber	Di(2-ethylhexyl) phthalate (DEHP)	9.51 pg/L	0.05 to 100000 ng/L	Beaker based Anode is non-enzymatic glucose based which drives cathode based DEHP sensor.	93.2% after 30 days	38
$\text{Ti}_3\text{C}_2\text{T}_x$ MXene- TiO_2 composite photoanode	Prussian blue (PB) cathode	Ochratoxin A	0.0587 ppb	0.2 ppb–20 ppb	Beaker based $P_{\max}$: ~15.015 $\mu\text{W}/\text{cm}^2$ E_{OCV} : ~440 mV	85.2% of initial after 7 days	40
$\text{MoS}_2\text{-Ti}_3\text{C}_2\text{T}_x$ MXene heterojunction on indium tin oxide (ITO)	Hemin and graphene composite	Aflatoxin B1 (AFB1)	0.73 pg/mL	0.01–1000 ng/mL	Beaker based E_{OCV} : ~465 mV in PBS, Milk, Oil, and Maize	97% of initial after 7 days	41
$\text{Ti}_3\text{C}_2\text{T}_x/\text{ZnIn}_2\text{S}_4$ heterojunction photoanode	Cu_2O photocathode	Microcystin-RR (MC-RR)	0.033 pM	0.1 to 100 pM	Portable device $P_{\max}$: ~26 μW E_{OCV} : ~450 mV	Unchanged after continuous cycling every 7 days	42
BiVO_4 and V_2C MXene on fluorine-doped tin oxide (FTO)	Molybdate hexacyanoferrate (MoHCF)	Chloramphenicol	0.17 pM	0.5 pM to 3 nM	Beaker based $P_{\max}$: 0.626 $\mu\text{W}/\text{cm}^2$ under light irradiation	97.99% signal after 6 cycles every 2 days	43
V_2CT_x MXene and bimetallic CoNi-layered double hydroxide (CoNi-MLDH) heterojunction	Zinc (Zn) plate anode	Cortisol	0.17 fg mL^{-1}	10 fg mL^{-1} to 100 ng mL^{-1}	Device based on glass substrate E_{OCV} : 1130 mV	98.49% after 15 days	46
Zinc (Zn) plate photoanode	Cadmium-doped MoS_2 on $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (Cd- $\text{MoS}_2@ \text{Ti}_3\text{C}_2\text{T}_x$) heterojunction photocathode	Penicillin G	0.06 fg mL^{-1}	1.0 fg mL^{-1} to 0.1 ng mL^{-1}	Beaker based $P_{\max}$: ~2500 $\mu\text{W}/\text{cm}^2$ E_{OCV} : ~1100 mV	96.4% after 20 days	47



Pencil graphite-MWCNT/Pyrroloquinoline quinone-dependent glucose dehydrogenase (PQQGDH)	Pencil graphite-MWCNT/Bilirubin Oxidase (BOx)	Glucose	0.084 mM	Upto 1 mM	Beaker based $P_{\text{max}}: \sim 2.5 \mu\text{W}/\text{cm}^2$ $E_{\text{OCV}}: \sim 450 \text{ mV}$	94% after 12 days	⁵⁶ View Article Online DOI: 10.1039/D5TA06598D
Carbon paper (CP) / ultrathin hollow carbon shells (UHCS) / gold nanoparticles (AuNPs) / polydopamine film / laccase	DNA1/UHCS/AuNPs/CP	L-Cysteine	2.2 nM	0.01–5 μM	Beaker based $E_{\text{OCV}}: \sim 360 \text{ mV}$	97% after 2000 s	⁵⁷
Carbon cloth /AuNPs/Graphdyne/glucose oxidase/Bovine serum albumin	Carbon cloth /AuNPs/Graphdyne/AuNPs/T-DNA/MCH/DNA nanorods	miRNA-141	21.9 aM	0.0001 to 100 pM	Beaker based $E_{\text{OCV}}: \sim 175 \text{ mV}$	96.0- 97.3% after 12 days.	⁵⁸
Crystalline polymeric carbon nitride/SWCNT film	SWCNT/Pt NPs	Peroxide	0.006 mM	0 mM–1.0 mM	Microfluidic based Photoelectrochemical sensing mechanism regulated by electrocatalytic current	Unchanged for 7 days	⁵⁹

6. Stability Of MXenes

The chemical and environmental vulnerability of MXenes when exposed to air or water significantly restricts their deployment in practical systems. Surface groups such as hydroxyl, oxygen and fluorine form reactive sites that initiate oxidation. Researchers therefore pursue two main approaches. One aims to improve the intrinsic resilience of MXene by refining synthesis and reducing defect density. The other focuses on post synthesis stabilization through controlled storage conditions, antioxidant additives or protective coatings.

6.1. Thermodynamic Stability of MXenes

MXenes exhibit significant thermodynamic instability due to their high surface energy, which makes them prone to degradation even under mild conditions. Surface terminations such as -OH, -O, or -F, commonly present in MXenes, further aggravate this issue by increasing their reactivity with environmental agents. For example, $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes are particularly prone to oxidation in ambient conditions, leading to the formation of titanium dioxide (TiO_2) and a loss of electrical conductivity. Studies have shown that even brief exposure to air can result in measurable degradation, with oxidation rates heavily influenced by the density and type of surface terminations. Elevated temperatures accelerate these transformations, with thermal decomposition often leading to the

conversion of MXenes into metal oxides completely and this phenomenon is particularly problematic for high-temperature applications. For instance, $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes, when subjected to temperatures above 400 °C, decompose into anatase or rutile TiO_2 , as reported in thermal stability studies ⁶⁰.

The degree of hydrophilicity observed in these materials was found to depend heavily on both the etching medium, whether a single acid like HF or a combination such as H_2SO_4 and HF or HCl and HF. Interestingly, $\text{Ti}_3\text{C}_2\text{T}_x$, exhibited a greater retention of structural water when fewer oxygen-based terminations were present on the surface. Furthermore, employing milder etching conditions or mixed acid systems led to improved thermal robustness by minimizing defect sites during synthesis. The thermal durability of MXenes is closely linked to their intrinsic structure and elemental makeup. Among them, $\text{Ti}_3\text{C}_2\text{T}_x$ exhibits superior heat resistance compared to Mo_2CT_x and Nb_2CT_x , both of which possess fewer atomic layers. Between the latter two, Mo_2CT_x is thermally more robust than Nb_2CT_x ⁶¹.

6.2. Key Influences on the Oxidative Stability of MXenes

The stability of MXenes is strongly influenced by their intrinsic chemical composition and microstructural features, particularly the type of metal layers and the surface terminations. Zhang et al. examined the oxidation response of $\text{Nb}_4\text{C}_3\text{T}_x$ MXenes in a CO_2 atmosphere at 850 °C and reported the development of a



multilayered structure decorated with uniformly distributed Nb₂O₅ nanoparticles across the nanosheet surface. Their study revealed that Nb₄C₃T_x is considerably more resistant to oxidation than Ti₃C₂T_x, which undergoes oxidation at much lower temperatures, around 500 °C, under CO₂ flow⁶².

Numerous research ideas have highlighted the structural integrity of MXenes is governed by a combination of external chemical conditions and inherent material properties, such as atmospheric exposure, temperature, compositional variations, microstructural features, and interactions with aqueous environments. Furthermore, even MXenes sharing the same chemical composition can display markedly different oxidation behaviours, primarily due to variations in their synthesis techniques and processing conditions.

Extensive investigations have been carried out to understand the thermal and chemical stability of MXenes under different atmospheric conditions such as vacuum, inert, oxidizing, and reducing environments. For instance, Ti₃C₂ MXenes have been reported to remain structurally stable in an argon atmosphere even at elevated temperatures up to 800 °C. In contrast, when subjected to oxygen-rich conditions, oxidation begins at relatively low temperatures (200 °C), leading to the uniform formation of anatase across the surface. Upon heating to 1000 °C, this anatase phase further transforms completely into rutile^{63,64}. A detailed evaluation of V₂CT_x MXenes was carried out by Thakur et al., who examined their stability in air, CO₂, H₂, and N₂ atmospheres at temperatures up to 600 °C. They reported that above 300 °C, V₂CT_x readily oxidized in air or CO₂, producing V₂O₅ and other VO_x phases, along with a complete collapse of the layered architecture. Under a reducing H₂ atmosphere, however, partial retention of the layered structure was observed. Exposure to N₂ led to mild oxidation, attributed to trace H₂O molecules incorporated during the synthesis process, which reacted with the surface groups of V₂CT_x⁶⁵.

The oxidation of MXenes occurs more rapidly when they are dispersed in aqueous media compared to their freestanding form. Earlier studies attributed this instability mainly to dissolved O₂ in water. However, more recent evidence suggests that MXenes are inherently more reactive toward H₂O molecules than toward dissolved oxygen⁶⁶. Beyond neutral solutions, investigations have extended to alkaline and oxidizing environments. Doo et al. demonstrated that pH plays a critical role in dictating the oxidation pathway of aqueous Ti₃C₂ dispersions. They proposed a distinct

mechanism in which the terminal –OH groups interact with either H⁺ or OH[–] ions, generating different reaction intermediates depending on the pH⁶⁷. Complementing this, Zhao et al. showed that alkaline conditions accelerate MXene oxidation, where hydroxyl ions significantly enhance the conversion of Ti species. This conclusion was supported by XPS analysis, which revealed an increased proportion of Ti (IV) species in basic media⁶⁸. The stability and performance of MXenes depend on multiple factors including the method of synthesis, the nature of surface terminations, structural stability, and particle size, all of which need to be carefully optimized to ensure their effective use in a wide range of applications.

6.3. Extending the Lifetime of MXenes through Oxidation Mitigation

The limited stability of MXenes in ambient air and aqueous environments remains a key obstacle to their practical utilization. To overcome this challenge, significant research has focused on improving their resistance to degradation or alternatively designing systems that operate under non-aqueous conditions. This need has stimulated intensive efforts to suppress oxidation and structural breakdown, ultimately broadening the technological potential of MXenes. Reported approaches include strict regulation of storage environments and complete isolation from oxygen and moisture. In addition, the incorporation of antioxidant agents such as polyphosphoric anions and ascorbates has been shown to effectively slow down oxidation processes.

Oxidation in MXenes is often initiated at reactive surface terminations, particularly hydroxyl groups, which are highly vulnerable to oxidative attack. One approach to suppress this process involves the removal of surface terminations through thermal annealing under vacuum or inert environments. Such treatments enhance the inherent thermal stability of MXenes and extend their applicability in high-temperature settings. For instance, Wang et al. demonstrated that MXenes stripped of surface terminations could withstand heating up to 1200 °C under an argon atmosphere⁶⁹. Similarly, Zhao et al. reported that annealing Ti₃C₂T_x in argon promoted the formation of a thin, protective TiO₂ layer on the nanosheet surface. This oxide barrier, particularly effective in densely stacked films, restricted water penetration and preserved the internal structure. Compared to untreated Ti₃C₂T_x, the annealed films exhibited remarkable stability, maintaining their structure for



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over ten months in aqueous environments, thereby significantly expanding their potential in practical applications ⁷⁰.

In addition to thermal treatments, storage protocols play a crucial role in maintaining the integrity of MXenes. Studies have shown that both temperature and atmospheric composition directly affect their chemical stability. Zhang et al. recommended extending the lifetime of MXene dispersions by storing concentrated nanosheet suspensions with large lateral sizes in sealed, argon-filled containers at low temperatures ⁷¹. Other studies further highlighted that excluding dioxygen and refrigerating dispersions helps to minimize oxidative degradation. The solvent medium also influences stability: Maleski et al. compared $\text{Ti}_3\text{C}_2\text{T}_x$ dispersions in 12 different solvents and found that polar organic solvents such as DMF, NMP, PC, and ethanol significantly reduced oxidation compared to water. Similarly, isolation of MXene powders from aqueous suspensions via freeze-drying or vacuum filtration was reported as an effective approach to prevent aqueous-induced degradation. Collectively, these strategies demonstrate that careful optimization of storage conditions is essential for prolonging MXene lifetime in both solution and solid states ⁷².

Chemical modification and antioxidant incorporation represent another major pathway for enhancing MXene stability. Analogous to food preservation methods, antioxidants such as sodium L-ascorbate (NaAsc) have been employed to protect MXene dispersions. Zhao et al. showed that NaAsc forms a stabilizing layer around $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets, effectively inhibiting oxidation and maintaining their structure and conductivity for up to three weeks at room temperature ⁷³. Similarly, Natu et al. demonstrated that adding polyanionic salts (polyphosphates, polyborates, polysilicates) at low concentrations can suppress oxidation initiated at nanosheet edges by creating a protective electrostatic barrier ⁷⁴. Beyond antioxidants, functionalization with silanes ⁷⁵, polymer coatings ⁷⁶ and biomolecules such as silk fibroin ⁷⁷ has been shown to improve hydrophobicity, enhance interfacial interactions, and provide protective encapsulation against oxidative attack. Furthermore, nanoscale carbon coatings offer an effective route to stabilize MXenes during synthesis. Overall, surface functionalization strategies including antioxidants, polymers, proteins, and carbon coatings provide versatile and effective means to suppress oxidation while retaining the functional properties of MXenes, thereby

extending their performance in electrochemical and other applications. View Article Online
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When combined these approaches, process enhancement, solvent choice, antioxidant addition, thermal passivation and encapsulation dramatically extend the lifespan of MXene materials and help retain their electronic and structural properties. These advances pave the way for integration of MXene into real world SPECS devices enabling high efficiency, durable self-powered sensing in applications ranging from environmental monitoring to wearable diagnostics.

7. Conclusions

Self-powered electrochemical sensors (SPECS) offer a transformative solution by integrating energy generation along with analyte detection in which the output energy is in direct relation with the analyte concentrations, paving the way for next-generation devices. The successful realization of high-performance SPECS relies on advanced materials which are capable of efficiently supporting in both energy conversion and analyte recognition. Among the emerging candidates, 2D MXenes have gathered substantial attention and demonstrated remarkable potential in enabling diverse and highly effective SPECS platforms. This review discusses about the role of MXenes in various self-powered electrochemical sensors such as EBFC, MFC and BPECs. The unique combination of properties inherent to MXenes such as metallic conductivity and 2D structure can enhance charge transfer kinetics and charge separation efficiency, which are vital for maximizing the output signal in self-powered sensors. In addition, the large surface area and functionalized surface of MXenes makes them as a superior scaffold for immobilizing a wide range of active components including enzymes, aptamers etc. Furthermore, the surface of MXene can act as a template for the in situ growth of other functional materials, which can create heterojunctions with improved photocurrents and photoelectric conversion efficiencies. The high electrochemical capacitance of certain MXenes can be used to deliver large instantaneous currents for effectively amplifying the sensitivity of self-powered electrochemical sensors.

The future trajectory for MXene-based SPECS is exceptionally bright, contingent upon addressing the current limitations. The challenges of long-term operational stability and degradation (Section 5) can be overcome by focusing future research on precise surface engineering



and the rational design of novel heterostructures (Section 7). To combat the issue of reproducible, scalable, and cost-effective synthesis (Section 5), future efforts should be directed toward scalable micro/nanofabrication techniques for device miniaturization (Section 7). Furthermore, the limited understanding of charge transfer mechanisms and the integration of multiple components into miniaturized, robust devices (Section 5) necessitates a deeper fundamental investigation into these systems to unlock the full potential of MXenes for creating transformative autonomous sensing devices. By explicitly addressing these limitations through concerted research and development efforts, the field can transition from laboratory successes to impactful real-world applications.

8. Limitations and Future Prospects

Despite this rapid progress and demonstrated potential, several challenges impede the widespread practical application of MXenes in self-powered electrochemical sensors. Ensuring long-term operational stability of MXenes and resistance to degradation or oxidation, particularly in complex biological or environmental media will be a critical concern. The synthesis procedures should be modified to get reproducible, scalable, and cost-effective MXenes with precisely controlled properties are highly needed for commercial viability. The ongoing research should focus into precise surface engineering of MXenes to tailor functional groups towards achieving specific recognition and the rational design of novel heterostructures for getting the maximum synergistic effects. To enable testing and validation of MXene based SPECS at higher TRLs, future work must focus on stabilising MXenes with antioxidants, polymers, proteins, and carbon coatings. These strategies will help suppress oxidation related degradation of the MXene layer, thus helping long term anchoring of bioreceptors thus maintaining the performance characteristics of the SPECS. Another key research direction in this vein involves not only tailoring MXenes with functional groups for biorecognition element immobilisation but also developing methods to synthesize MXene-molecularly imprinted polymer (MIPs) composites. This strategy will help to bypass limitations associated with conventional bioreceptors like aptamers and antibodies, while exhibiting the same specificity. A synergy between enzyme driven power production and MXene-MIP composite-based sensing is a promising approach in this direction.

Towards improving energy conversion efficiencies, MXene integrated energy storage systems with better power management and exploring hybrid energy harvesting modes along with advancing scalable micro/nanofabrication techniques for device miniaturization need to be considered. For rational design optimization of MXene based systems, a deeper fundamental understanding of charge transfer mechanisms and synergistic effects in complex MXene-based systems should be thoroughly investigated. Moreover, the effective energy management solutions should be applied for certain high-demand applications and the significant engineering challenges in the integration of multiple components into miniaturized, robust devices need to be solved.

Further exploration could involve MFCs, which have been realized using diverse electrode materials and are being considered for wearable and environmental sensing⁷⁸⁻⁸¹. Given that MXenes have already demonstrated success in MFC device realization, attributable to their high electrical conductivity, large active surface area, inherent biocompatibility, and ability to facilitate efficient extracellular electron transfer (EET). The focused application of MXene-based MFCs for self-powered wearable and environmental sensing presents a compelling, yet relatively underexplored, research avenue.⁸²⁻⁸⁴ Future reports could specifically address this niche, bridging the gap in leveraging these advanced MXene-MFC systems for such targeted sensing applications. Similarly, a parallel research thrust could explore applications of MXenes in self-powered devices integrating photosynthetic systems. This could involve employing isolated photosynthetic receptors (like thylakoids),⁸⁵ or whole microorganisms,⁸⁶ such as algae,⁸⁷ phytoplankton,⁸⁸ and potentially engineered yeast strains, thereby opening further avenues for novel bio-hybrid sensor development—an area also warranting deeper future investigation, including the potential role of MXenes in enhancing such photosynthetic bio-interfaces.

Nevertheless, the future trajectory for MXene-based SPECS is exceptionally bright for translating laboratory successes into impactful real-world applications. By addressing the current limitations through these concerted research and development efforts, the field of MXene-based SPECS can unlock the full potential of MXenes to create truly transformative autonomous sensing devices for diverse applications.



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Data availability statement

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The data are made available as per the request

