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# Peer Review File

# Progress towards efficient MXene sensors

Corresponding Author: Professor Joselito Razal

**This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.**

Version 0:

Decision Letter:

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Dear Professor Razal,

Thank you for submitting your manuscript, "Exploring the Challenges and Opportunities in MXene Sensor Development", to Communications Materials. It has now been seen by 3 referees, whose comments are appended below. You will see that while they find your work of interest, some important points are raised. We are interested in the possibility of publishing your study in Communications Materials, but would like to consider your response to these concerns in the form of a revised manuscript before we make a decision on publication.

We therefore invite you to revise and resubmit your manuscript, taking into account the points raised.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

When submitting your revised manuscript, please include the following:

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We hope to receive your revised paper within three months; please let us know if you aren’t able to submit it within this time so that we can discuss how best to proceed. If we don’t hear from you, and the revision process takes significantly longer, we will close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Materials or published elsewhere in the meantime.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Mengqiang Zhao
Guest Editor
Communications Materials

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The paper is well written. All the relevant sections are well addressed.
The paper was quite informative and had a nice introduction and very well driven conclusion.

Reviewer #2 (Remarks to the Author):

The article systematically reviews the challenges and opportunities of MXene in sensor development, covering various types of sensors such as physical, chemical, and optical sensors. It comprehensively analyzes the unique properties of MXene, such as high electrical conductivity and surface tunability, as well as its application potential in sensors. The discussion of existing problems in the article, such as oxidative degradation and difficulties in large-scale production, is of practical significance, and feasible solutions are proposed, providing an important reference for subsequent research. Overall, the manuscript is well organized. I would like to recommend publishing in the Communications Materials after some revisions.
1# The article should include a detailed comparison table of the performance indicators of traditional sensors and other novel sensors, covering key indicators such as sensitivity, detection limit, response time, stability, and cost, so that readers can intuitively understand the advantages and gaps of MXene-based sensors.
2# When studying the impact of the combination of MXene and other materials on the performance of the sensors, the control ranges and optimization processes of variables such as the compounding ratio and the preparation process are not clearly specified, which affects the reliability and reproducibility of the experimental results. Relevant information needs to be supplemented.
3# In the section on optical and spectroscopic sensors, there is a lack of in - depth exploration regarding how the plasmonic properties and electronic structure of MXene precisely influence the light - matter interaction, as well as the variation patterns of this interaction under different detection scenarios.
4# The authors may consider discussing more new papers on MXene based novel optoelectronic devices for a broader readership.
5# The article points out that MXene is prone to oxidation in water and humid environments, which affects the long-term stability of the sensor. However, the research on the stability of MXene in different practical application scenarios is not comprehensive enough. In wearable devices, MXene-based sensors are frequently affected by factors such as human sweat and friction. How do these factors work together to accelerate the oxidation of MXene and the degradation of its performance? In addition, although some methods to improve stability, such as surface passivation and protective coatings, are mentioned in the article, the effectiveness and durability of these methods during long-term use lack the support of long-term experimental data. For MXene-based sensors treated with surface passivation, will the passivation layer gradually fail when used continuously for several months or even years? And what is the failure mechanism?

Reviewer #3 (Remarks to the Author):

The current review article presents an overview of the challenges and opportunities in the development of MXene-based sensors. While numerous review articles have already been published on the potential applications of MXenes, this manuscript distinguishes itself by placing greater emphasis on the challenges associated with their practical implementation. Overall, the manuscript is well-written and logically structured, with appropriate division into sections and subsections. The quality of the figures and the language used is commendable.
However, the following points should be carefully considered before moving to the next stage of the review process:
1. Although the manuscript is intended to highlight the challenges, much of the focus is still on the potential applications of MXene-based sensors. In particular, the issue of long-term stability — a critical factor hindering real-world applications — requires greater emphasis. While the section “Addressing MXene stability issues” touches on strategies such as passivation layers and coatings, the descriptions are relatively brief. The authors are encouraged to expand this section with more in-depth discussion, supported by literature evidence, on methods to improve the long-term stability of MXenes in sensor applications.
2. Scalability is another significant limitation in the practical deployment of MXene-based sensors. The authors are advised to elaborate on the challenges associated with large-scale synthesis and integration, and to discuss potential solutions or advancements in this area.
3. While artificial intelligence (AI) is mentioned as a potential solution, it should be noted that without reliable and stable sensor systems, the quality of training datasets will be compromised. This would, in turn, hinder the effectiveness of AI models in real-world applications. The manuscript should reflect on this interdependency more clearly.

4. Please consider adding a brief statement in the abstract to highlight the major challenges of MXene-based sensors, in order to align the summary with the main focus of the review.

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Version 1:

Decision Letter:

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Dear Professor Razal,

Thank you for submitting your revised manuscript, "Exploring the Challenges and Opportunities in MXene Sensor Development". We have assessed your replies to the comments of the referees and i am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Materials.

We therefore invite you to edit your manuscript to comply with our journal policies and formatting style in order to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS
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We hope to hear from you within two weeks; please let us know if the process may take longer.

Best regards,

Mengqiang Zhao, PhD
Guest Editor
Communications Materials

# Response to reviewer(s)' comments

(Manuscript ID **COMMSMAT-25-0138**)

**General response:** We sincerely thank the reviewers for their valuable time and insightful comments. We have carefully considered all suggestions and incorporated the key revisions, which are highlighted in blue throughout the manuscript. We believe their feedback has greatly improved the quality of our work.

**Reviewer #1:** The paper is well written. All the relevant sections are well addressed.
The paper was quite informative and had a nice introduction and very well driven conclusion.

Response:

Thank you for your thoughtful and encouraging feedback. We are pleased to hear that you found the paper both informative and well-structured. Your kind words are greatly appreciated.

**Reviewer #2:** The article systematically reviews the challenges and opportunities of MXene in sensor development, covering various types of sensors such as physical, chemical, and optical sensors. It comprehensively analyzes the unique properties of MXene, such as high electrical conductivity and surface tunability, as well as its application potential in sensors. The discussion of existing problems in the article, such as oxidative degradation and difficulties in large-scale production, is of practical significance, and feasible solutions are proposed, providing an important reference for subsequent research. Overall, the manuscript is well organized. I would like to recommend publishing in the Communications Materials after some revisions.

1. The article should include a detailed comparison table of the performance indicators of traditional sensors and other novel sensors, covering key indicators such as sensitivity, detection limit, response time, stability, and cost, so that readers can intuitively understand the advantages and gaps of MXene-based sensors.

Response:

Thank you for your insightful suggestion. In response, we have added detailed comparison tables to clearly highlight the key performance indicators and better illustrate the strengths and limitations of MXene-based sensors. For clarity, the information is organized into three separate tables, each representing a specific sensor category. The properties of MXene-based sensors are highlighted in bold for easy reference.

*(Manuscript Pages 6-9)*
In this section, we discuss common types of MXene-based physical sensors, including strain, pressure, acoustic, and temperature sensors. We also provide a comprehensive summary of representative examples in Table 1.

**Table 1**. Representative studies on physical sensors, including performance comparisons with existing materials reported in the literature.

| Type | Material/s | Contains MXene? | MXene load | Sensitivity (S) / Gauge Factor (GF) | Sensing / Detection range | Response time | Recovery time | Stability / Load-unload cycles | Ref |
|---|---|---|---|---|---|---|---|---|---|
| **Strain sensors** | Graphene-PDMS films | No | - | S = 1875.53 $kPa^{-1}$ (0 to 20 kPa); 853.2 kPa (20 to 40 kPa) | 0 to 40 kPa | 0.5 ms | 0.8 ms | 15,000 | [1] |
| | PEDOT:PSS microchumps | No | - | S = 931.6 to 770.4 $kPa^{-1}$ (<1.5 kPa); 770.4 to 51.3 $kPa^{-1}$ (1.5 to 15 kPa); 51.3 to 31.9 $kPa^{-1}$ (15 to 20 kPa) | 34 Pa to 20 kPa | 0.15 ms | - | 20,000 | [2] |
| | CNTs-TPU fibers | No | - | GF = 2.51 (10% strain); 166.7 (350% strain) | 10 to 350% | 167 ms | - | 10,000 | [3] |
| | PAM organo-hydrogel | No | - | GF =98.3 (0 to 1.5%); 131 (1 to 40%); 1275 (40 to 90%) | 0.05 to 90% | 147 ms | 147 ms | 2,100 | [4] |
| | **$Ti_3C_2T_x$ MXene/PU Fibers** | **Yes** | **1-30 wt. %** | **GF = 12900 (0 to 152%); 238 (0 to 50%)** | **0 to 152 %** | **-** | **-** | **1,000** | [5] |
| | **$Ti_3C_2T_x$ MXene/graphene films** | **Yes** | **<50 %** | **GF = 1148.2 (52.6 to 74.1%); 190.8 (0 to 56.2 %)** | **0 to 74.1 %** | **130 ms** | **-** | **5,000** | [6] |
| | **Spin-coated $Ti_3C_2T_x$ MXene on PU nanofiber mat** | **Yes** | **Complete coverage of the fiber mat surface** | **GF= 228 (0 to 150 %)** | **58 to 150%** | **-** | **-** | **3,200** | [7] |

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| | **Spin-coated $Ti_3C_2T_x$ MXene on PU/PAN nanofiber mat** | **Yes** | **Complete coverage of the fiber mat surface** | **GF= 9.69 (0 to 80 %)** | **0 to 80 %** | **<140.6 ms** | **-** | **1,750** | [8] |
| | **TPU/CNTs@MXene** | **Yes** | **10 wt.% MWCNTs (30 x 5 $mm^2$) soaked in 4 mg $mL^{-1}$ MXene solution.** | **GF = 13 (0 to 40%); 73 (40 to 80%); 363 (80 to 101%)** | **0 to 100%** | **Real-time** | **-** | **200** | [9] |
| | **GnP-MXene coated Poly(styrene–butadienestyrene) nanofiber mat (Cellulose nanocrystals as binder)** | **Yes** | **Complete coverage of the fiber mat surface (0 to 50 wt. % of the coating formulation)** | **FG= 400 (at 100%); 76.1 (at 10%)** | **0 to 200%** | **100 ms** | **100-120 ms** | **2,000** | [10] |
| **Pressure sensors** | $PVA/H_3PO_4$ | No | - | S = 3302.9 $kPa^{-1}$ (<10 kPa); 671.7 $kPa^{-1}$ (10 to 100 kPa); 229.9 $kPa^{-1}$ (100 to 360 kPa) | 0.08 Pa to 400 kPa | 9 ms | 18 ms | 2,000 | [11] |
| | Graphene | No | - | S = 229.8 $kPa^{-1}$ (0 to 0.12 kPa); 26.9 $kPa^{-1}$ (0.4 to 1 kPa) | 0 to 1 kPa | - | ~1084.6 mm $s^{-1}$ (recovery speed) | 100,000 | [12] |
| | **$Ti_3C_2T_x$ MXene/r-GO aerogels** | **Yes** | **20:1, 10:1, 5:1 MXene : r-GO ratios** | **22.56 $kPa^{-1}$** | **<10 Pa** | **~200 ms** | **~200 ms** | **10,000** | [13] |
| | **$Ti_3C_2T_x$ MXene/poly(vinylidene fluoride-trifluoroethylene) (PVDF-TrFE)** | **Yes** | **13 wt. %** | **0.51 $kPa^{-1}$** | **1.5 Pa to 400 kPa** | **-** | **-** | **10,000 at >167 kPa** | [14] |
| | **$Ti_3C_2T_x$ MXene-coated cellulose yarns** | **Yes** | **77 wt. %** | **GF= 6.02 (at 20% compression) 7.67 $kPa^{-1}$** | **0 to 20%** | **35 ms** | **-** | **2,000** | [15] |

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| | **MXene/PU** | **Yes** | **MXene colloidal solution was uniformly sprayed on the PU surface until the surface resistance is ~5.0 to 30.0 Ω.** | **S = 281.54 $kPa^{-1}$ (0.20 to 1.70 kPa); 509.8 $kPa^{-1}$ (1.0 to 5.70 kPa); 66.68 $kPa^{-1}$ (5.70 to 20.30 kPa)** | **0.20 to 20.30 kPa** | **67.3 ms** | **44.8 ms** | **10,000** | [16] |
| | Ag NWs/Graphene/PANFs | No | - | S = 134 $kPa^{-1}$ (0 to 1.5 kPa); 0.7 $kPa^{-1}$ (15 to 75 kPa) | 0 to 75 kPa | 20 ms | - | 8,000 | [17] |
| | **MXene/Ionic film** | **Yes** | **The dried n-WF was immersed in MXene solution (5 mg $mL^{-1}$) for 10 s and dried at 50 °C repeated 4 times.** | **S = 200 $kPa^{-1}$ (<60 kPa); 5,000 $kPa^{-1}$ (60-200 kPa); 46,730 $kPa^{-1}$ (200-800 kPa); 17,148 $kPa^{-1}$ (<1.4 MPa)** | **20 Pa to 1.4 MPa** | **98 ms** | **70 ms** | **10,000** | [18] |
| **Acoustic Sensors** | PVDF | No | - | S = 266 mV $Pa^{-1}$ | - | - | - | - | [19] |
| | Lead-free perovskite | No | - | S = 150.63 mV $Pa^{-1}$; 39.22 mV $Pa^{-1}·cm^{-2}$ | 100 to 3,000 Hz | - | - | - | [20] |
| | Triboelectric nanogenerator (TENG) | No | - | S = -30 ± 3 dB | 20 to 20,000 Hz | Real-time | - | - | [21] |
| | Epoxy resin/Al film | No | - | S = 11.1 mV $Pa^{-1}$ $mm^{-2}$ | 15 to 10,000 Hz | Real-time | - | - | [22] |
| | **MXene-PDMSP-PE** | **Yes** | **The MXene solution was spin-coated on the PDMS-PE substrate.** | **S = 62 $kPa^{-1}$** | **150 Hz to 3 kHz** | **15 ms** | **25 ms** | **-** | [23] |
| | **MXene/$MoS_2$** | **Yes** | **0.5 mL MXene (1 mg $mL^{-1}$) and 0.5 mL $MoS_2$ (1 mg $mL^{-1}$) evenly sprayed on nitrile powder-free gloves.** | **S = 25.8 mV/dB** | **40 to 3,000 Hz** | **4 ms** | **-** | **-** | [24] |
| **Temperature Sensors** | **MXene/PEI** | **Yes** | **The optimal MXene concentration (0.8 mg $mL^{-1}$) was used to prepared the MXene/PEI fibrous network with 1.5 x 1.5** | **S = -5 °C (80 $kPa^{-1}$) to 150 °C (20 $kPa^{-1}$)** | **-5 °C (liquid $N_2$) to 150 °C** | **163 ms** | **-** | **10,000 at RT; 2,000 at 100 °C; and 500 at -5 °C** | [25] |

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| | | | **$cm^2$ size fixed onto a Cu-coated electrode.** | | | | | | |
| | ITO-$In_2O_3$-$Al_2O_3$ | No | - | S = 129.80 μV / °C | 25 to 1300 °C | 3.52 ms | - | - | [26] |
| | Rubber/CNT | No | - | GF = 25.98 | 30 to 100 °C | 200 ms | - | - | [27] |
| | Pt/$In_2O_3$ | No | - | S = 204.35 μV / °C | - | 2010 ms | - | - | [28] |
| | PEDOT:PSS-PDMS | No | - | S = 0.042 $°C^{-1}$ | 30 to 55 °C | Real-time | - | - | [29] |
| | **MXene-PDMAEMA** | **Yes** | **The MXene-PDMAEMA thin films have varying thicknesses between 20 and 80 μm.** | **S = 0.8 mS** | **25 to 40 °C** | **-** | **-** | **-** | [30] |
| **Photo-sensitive sensors** | Ga-doped $In_2O_3$ | No | - | S = 7.6 x $10^4$ | 915 to 1,550 nm | 30 ms | 10 ms | - | [31] |
| | PM6:TPDC-4F | No | - | D* = 1.27 x $10^{13}$ cm $Hz^{1/2}$ at 800 nm | 300 to 900 nm | 6.81 μs | 5.41 μs | - | [32] |
| | Graphene/PM6:Y6 | No | - | D* = 1.47 x $10^{14}$ Jones at 650 nm | 488 to 895 nm | 20 μs | 8.4 μs | - | [33] |
| | **Paraffin wax-MXene** | **Yes** | **MXene films with thickness of ~6 μm put on a solid PW coated on a glass slide.** | **S = 4.6 $m^{-1}$/ °C** | **-** | **380 ms** | **-** | **>20,000** | [34] |
| | **LDPE/MXene** | **Yes** | **The MXene dispersion (5 mg $mL^{-1}$) was uniformly sprayed on the surface of the LDPE film.** | **S = 38 mW $cm^{-2}$** | **-** | **-** | **-** | **-** | [35] |
| D* = Detectivity | | | | | | | | | |

*(Manuscript Pages 20-21)*

**Table 2**. Representative studies on chemical sensors, including performance comparisons with materials reported in the literature.

| Type | Material | Analyte | Contains MXene? | MXene load | Linear range | LOD/ Sensitivity | Response/ recovery time | Stability | Notes | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| Chemiresistive | CuO NSs + $CeO_2$ NPs | $NO_2$ gas (100°C) | No | - | 200 ppb to 600 ppt | 600 ppt | 15 s to 10 ppm $NO_2$ | 30 days | Also demonstrated that the sensor operates at 100°C | [36] |
| | Pd-$SnO_2$ NPs | Toluene | No | - | 1 to 10 ppb | 200 ppt (initial resistance curve) | Not specified | Not specified | 2 sensing mechanisms based on the pulse | [37] |
| | PEDOT:PSS/$TiO_2$/ZnO NWs | $H_2$ | No | - | 1 to 20 ppm | 9 ppt at 50°C, 1 ppb at 25°C | 65 s to 100 ppb $H_2$ | 9 months | Flexible sensor, works even at 50°C | [38] |
| | **$Ti_3C_2T_x$ MXene film (vacuum-dried) w/ Au contacts** | **VOC gases: acetone, ethanol, ammonia, and propanal, $NO_2$, $SO_2$, $CO_2$** | **Yes** | **Not specified (>400mg)** | **Not specified** | **50 to 100 ppb at RT** | **Not specified** | **Not specified** | | [39] |
| | **MXene** | **Microcystin-LR in water from cyanobacteria *Microcystis aerouginosa*** | **Yes** | **0.025 mg (thin coating only)** | **1 to 104 ng $L^{-1}$** | **0.18 ng $L^{-1}$** | | | | [40] |
| | **MXene** | **$W_{18}O_{49}$ NRs/ $Ti_3C_2T_x$ MXene nanocomposites** | **Yes** | **2 wt. % MXene** | **0.17 to 500 ppm** | **170 ppb** | **5.6 s/6s** | **Tested for 100 cycles** | | [41] |
| Capacitive | GO | RH | No | - | 40-99% RH | 8504% (C/Co) at 500 Hz | 170/40 s | 15 days | | [42] |

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|---|---|---|---|---|---|---|---|---|---|---|
| | MWCNT | RH | No | - | 10to 90% RH | ~1480% (Δ*C*/*C*0) | 0.8/0.78 s | 48 h/2 days | | [43] |
| | ZrP nanoplates | RH | No | - | 10.9 to 91.5% RH | 2409 (C/Co) @ 100 Hz | x/9 s | 4 wk | | [44] |
| | **MXene-decorated Flower like $SnS_2$, in situ hydrothermal** | **RH** | **Yes** | **30 wt. % MXene** | **7-93% RH** | **433,827.42 % (ΔC/Co) at 1 kHz** | **22.5 s/0.21 s** | **15 days** | | [45] |
| | **$Ti_3C_2$/Ag hybrid on PDDA substrate** | **RH** | **Yes** | **98 wt. % MXene (2 wt. % Ag)** | **35–95% RH** | **106,800% (ΔC/Co)** | **80/120 ms** | **40 days** | | [46] |
| **Electrochemical** | SFB-imprinted poly-methyldopa on PGE | Sofosbuvir | No | - | 10 to 0.1 pM | 0.031 pM | 30 s | 3 days | RSA on plasma & (pharmaceutical) tablet samples | [47] |
| | ENR-imprinted APTES-based polymer on MWCNT on GCE | Enrofloxacin | No | - | 2.8 pM to28 μM | 0.9 pM | Not specified | 7 days | RSA on seaweater samples | [48] |
| | Cortisol-specific antibodies on $SnO_2$ nanoflake-integrated conductive carbon fiber ($SnO_2$/CCY) | Cortisol | No | - | 10 fg $mL^{-1}$ to 1 μg $mL^{-1}$ | 1.6 fg $mL^{-1}$ | Not specified | 1 month | Indirect sensing using ferrocyanide probe; RSA on sweat | [49] |
| | **Pt/$MoS_2$/$Ti_3C_2$ MXene on GCE** | **Methyl parathion, chlorpyrifos, dimethoate** | **Yes** | **Not specified (~1/3 of composite load)** | **1 pM to 1 μM** | **0.471 pM** | **Not specified** | **7 days** | **RSA on fruits & veggies** | [50] |
| | **Cortisol-imprinted poPD on MXene/graphene composite** | **Cortisol** | **Yes** | **33 wt. % MXene in the MXene/graphene composite** | **1 fM to 10 μM** | **0.4 fM** | **Not specified** | **1 month** | **RSA on saliva** | [51] |
| | **DNA nanostructure/MXene nanocomplexes** | **Gliotoxin** | **Yes** | **10 vol. % MXene** | **5 pM to 10 nM** | **5 pM** | **Not specified** | **Not studied** | | [52] |

*(Manuscript Pages 28-29)*

**Table 3**. Representative studies on optical sensors, including a comparative analysis of their performance against materials currently reported in the literature.

| Type | Material | Laser | Analyte | Contains MXene? | MXene load/ thickness | Linear range | LOD/Sensitivity/Enhancement | Recovery range/ Reproducibility | Stability | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| **SPR** | $MoS_2$ + Au | N | human IgG | No | - | 5 to 20 µg $mL^{-1}$ | 19.7 ng $mL^{-1}$ | Not specified | Tested for 5 cycles | [53] |
| | Muti-single Fiber | 633 nm | glucose | No | - | 0 to 10 mmol $L^{-1}$ | 0.12 mM $L^{-1}$, 2.819 nm $mM^{-1}$ | Not specified | Not specified | [54] |
| | GO + Au NPs | 400 to 1000 nm | DNA | No | - | 1 to 1000 fmol | 0.2 fM, 11773.93 nm per RIU | Not specified | Not specified | [55] |
| | **Au + $Ti_3C_2T_x$ MXene** | **633 nm** | **N** | **Yes** | **Not specified/ 4 layers** | **N** | **160 ° per RIU, 16.8%** | **N** | **N** | [56] |
| | $Ti_3C_2$ MXene + AuNPs | 633 nm | Carcinoembryonic antigen | No | - | 20 fM to 20 nM | 0.07 fM | 98.2% to 111.1% | 7 days | [57] |
| **SERS** | GO + Au NPs | 633 nm | ampicillin | No | - | 1 ng $ml^{-1}$ to 0.01 ng $ml^{-1}$ | 0.01 ng $mL^{-1}$ | 4.79% Std | Not specified | [58] |
| | Au@Ag + Au | 633 nm 785 nm | Interleukin-6 (IL-6) | No | - | 100 fg $mL^{-1}$ to 1 ng $mL^{-1}$ | 12.4 fg $mL^{-1}$ | 92.4% to 105.3% | 30 days | [59] |
| | CuO@Ag NPs | 532 nm | thiram | No | - | 0.05 to 20 nmol $L^{-1}$ | 0.0067 nmol $L^{-1}$ | 93.9 to 112.3%, 10.33% Std | Not specified | [44] |
| | **TiC MXene-decorated Au NPs** | **532 nm** | **chlorpromazine (CPZ)** | **Yes** | **Not specified** | **0.1 nmol $L^{-1}$ to 0.1 mol $L^{-1}$** | **0.392 pmol $L^{-1}$** | **8.80% Std** | **15 days** | [60] |

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|---|---|---|---|---|---|---|---|---|---|---|
| | **$Ti_2C$ MXene/Au–Ag NSs** | **785 nm** | **carbendazim (CBZ)** | **Yes** | **99.5% MXene** | **0.033 to 10 µmol $L^{-1}$** | **0.01 µmol $L^{-1}$** | **2.77% Std** | **Not specified** | [61] |
| **Electrochemiluminescent and Photoluminescent** | Ag/r-GO/ZnO on nickel foam | N | $H_2O_2$ | No | No | 0.01 to 200 µmol $L^{-1}$ | 0.005 µmol $L^{-1}$ | 2.8 % Std | 25 days | [62] |
| | $MoS_2$/ZnO | N | Propyl gallate (PG) | No | No | 0.125 µmol $L^{-1}$ to 1.47 mmol $L^{-1}$ | 0.12 nmol $L^{-1}$ | 96% to 99.4% | cycles for 30 times | [63] |
| | Carbon quantum dots (CDs) | 365 nm EX/ 450 nm EM | $Fe^{3+}$ | No | No | 0.06 to 10 µmol $L^{-1}$ | 0.039 µmol $L^{-1}$ | Not specified | Not specified | [64] |
| | g-$C_3N_4$ | 457 nm EX/ 588 nm EM | $Zn^{2+}$ | No | No | 10 to 2000 µM | 1.8 µmol $L^{-1}$ | Not specified | Not specified | [65] |
| | **$TiO_2$/$Ti_3C_2T_x$ /Cu2O MXene** | **N** | **glucose** | **Yes** | **Not specified** | **100 nM to 10 mM** | **3.75 nM** | **Not specified** | **cycles for 400 s** | [66] |
| | **$BiVO_4$/ $Ti_3C_2T_x$** | **N** | **$Hg^{2+}$** | **Yes** | **Not specified** | **1 pM to 2 nM** | **1pM** | **90.7% and 109.3%** | **cycles for 600 s** | [67] |
| | **N-MQDs ($Ti_3C_2$)** | **380 nm EX/ 570 nm EM** | **$Cu^{2+}$** | **Yes** | **100%** | **0 to 1000 µM** | **3.0 nM** | **98.50 % to 101.97 %, 0.25 % to 3.68 % Std** | **30 days** | [68] |
| | **Aptamer-polyhedral oligomeric silsesquioxane-perovskite QDs/ $Ti_3C_2$ MXenes composite** | **480 nm EX/ 519 nm EM** | **Vibrio parahaemolyticus** | **Yes** | **Not specified** | **$10^2$ to $10^6$ CFU $mL^{-1}$** | **100 CFU $mL^{-1}$** | **93 and 106%, 2.7% to 6.7% Std** | **1 week** | [69] |

2. When studying the impact of the combination of MXene and other materials on the performance of the sensors, the control ranges and optimization processes of variables such as the compounding ratio and the preparation process are not clearly specified, which affects the reliability and reproducibility of the experimental results. Relevant information needs to be supplemented.

Response:

This is a valuable point. Detailed information on MXene content, fabrication techniques, and other relevant details can be found in Tables 1–3. We have also included references to guide readers to more in-depth studies. For specific examples highlighting MXene content and fabrication methods, please see our response to Comment #1. We have also added key notes throughout the text to emphasize how controlling these variables improves the reliability and reproducibility of the results.

(*Manuscript, Page 10-11*)

The selected fabrication technique, such as spin coating, printing, or layer-by-layer assembly, directly affects film uniformity, adhesion, and strain transfer efficiency between the MXene layer and the substrate. Inconsistent control of these factors can lead to significant variations in sensor output, increased hysteresis, accelerated fatigue, and ultimately, reduced performance and reproducibility across batches.

(*Manuscript, Page 11*)

Seyedin *et al*. demonstrated the continuous fabrication of wet-spun MXene/PU coaxial fibers, that are both highly conductive and stretchable. These fibers, featuring a MXene/PU core surrounded by a flexible PU sheath, exhibited a low percolation threshold of ~1 wt.% MXene and outstanding strain sensing capabilities, with a GF of ~12,900 at 152% strain. This coaxial design also enhanced the fibers' stability under cyclic deformation[5].

It is important to note that the amount of MXene incorporated critically affects the percolation network and gauge factor. Insufficient MXene loading can result in poor conductivity and low signal-to-noise ratios, while excessive loading may reduce sensitivity due to limited strain-induced resistance changes.

*(Manuscript pages 31-32)*

The performance of the proposed SPR biosensor strongly depends on the number of $Ti_3C_2T_x$ MXene layers. Increasing the layer count broadens the Au-based SPR curves due to electron energy loss and shifts the resonance angle through enhanced light absorption. Sensitivity improves significantly up to four MXene layers but tends to plateau beyond that, even when combined with other materials. For example, SPR sensors paired with gold, aluminum, and copper show limited sensitivity gains at $\lambda = 633$ nm, with enhancements of 28.4%, 46.3%, and 33.6% enhancements for 7, 12, and 9 MXene layers, respectively.[56].

A theoretical study using Finite Difference Time Domain (FDTD) simulations examined MXene layer thickness ranging from 1 to 10 layers and found that thickness significantly affects sensor sensitivity. Notably, the effect varies with surface termination. F-terminated MXene achieved the highest sensitivity at 133.39°/RIU[70].
Although direct experimental research on surface terminations in SPR sensors is still lacking, surface terminations are known to influence MXene's electronic structure. For example, outermost halogen terminations like -I, and -Br can gain electrons and convert to their elemental forms when used as cathodes in $Ti_3C_2I_2$ or $Ti_3C_2Br_2$[71]. This electronic transformation impacts the plasmonic properties of MXene[72].
Future experimental studies are expected to further explore how surface terminations affect SPR sensor performance, offering deeper insights into optimizing these materials.

3. In the section on optical and spectroscopic sensors, there is a lack of in - depth exploration regarding how the plasmonic properties and electronic structure of MXene precisely influence the light - matter interaction, as well as the variation patterns of this interaction under different detection scenarios.

Response:

Thank you for your insightful comment. We have revised the section to provide a clearer and more detailed explanation of how the plasmonic properties and electronic structure of MXenes affect light–matter interactions, with particular emphasis on their sensitivity to environmental stimuli.

*(Manuscript, Page 30-31)*

MXene-based SPR sensors are typically fabricated so that incident light interacts with the sensor chip through a prism positioned beneath the sensor substrate. The two most commonly used prism configurations are the Kretschmann and the Otto configurations[73]. In the Kretschmann configuration, light passes through the prism and reflects off a thin metal layer coated on its surface, exciting surface plasmons at a specific resonance angle. In contrast, the Otto configuration features a small air gap between the prism and the metal layer, where surface plasmons are excited by an evanescent wave.

To overcome challenges such as limited penetration depth and sensitivity, advanced designs like nearly guided wave SPR configuration have been introduced. The Otto setup offers greater durability under high intensity light due to its superior thermal resistance and reduced wear on the metal layer. However, it is more complex to implement, as it requires precise control of the air gap.

The Kretschmann configuration, on the other hand, is simpler to set up and is therefore preferred for standard applications involving moderate light intensity[74]. MXene's exceptional mechanical and thermal stability[75] makes it particularly well-suited for use in the Kretschmann configuration, further enhancing the performance and practicality of MXene-based SPR sensors.

*(Manuscript pages 31-32)*

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Future experimental studies are expected to further explore how surface terminations affect SPR sensor performance, offering deeper insights into optimizing these materials.

*(Manuscript pages 33)*

Beyond studies of pristine MXene substrates, integrating MXenes with noble metals has emerged as a promising strategy for enhancing SERS performance[76]. This approach leverages the plasmonic properties of noble metals alongside the unique electronic properties of MXenes, resulting in highly sensitive and versatile SERS platforms.

A prominent resonance around ~1.7 eV has become a key in understanding the signal enhancement mechanism, though its exact origin remains under investigation.[77] In the case of $Ti_3C_2T_x$, the near-infrared absorption peak at ~1.7 eV (800 nm) has been attributed to combination of interband transitions (IBT) and localized surface plasmon resonance (LSPR). Density functional theory (DFT) studies support the IBT hypothesis, highlighting the peak's sensitivity to surface terminations while showing it to be largely independent of particle size[78] and solvent environment[79].

Evidence for LSPR contributions includes the detection of transverse plasmonic resonances via STEM-EELS[77b] and voltage-induced blueshifts in electrochromic devices[80]. Ongoing and future studies are expected to clarify the underlying mechanisms and facilitate the continued development of MXene-based SERS substrates.

4. The authors may consider discussing more new papers on MXene based novel optoelectronic devices for a broader readership.

Response:

As noted in our response to Comment #3, we have added new examples to better highlight recent advancements in the field (please see the previous section for details). The additional examples suggested in Comment #1 have been thoroughly summarized in Table 3.

5. The article points out that MXene is prone to oxidation in water and humid environments, which affects the long-term stability of the sensor. However, the research on the stability of MXene in different practical application scenarios is not comprehensive enough. In wearable devices, MXene-based sensors are frequently affected by factors such as human sweat and friction. How do these factors work together to accelerate the oxidation of MXene and the degradation of its performance? In addition, although some methods to improve stability, such as surface passivation and protective coatings, are mentioned in the article, the effectiveness and durability of these methods during long-term use lack the support of long-term experimental data. For MXene-based sensors treated with surface passivation, will the passivation layer gradually fail when used continuously for several months or even years? And what is the failure mechanism?

Response:

Thank you for the thoughtful and constructive feedback. In response, we have expanded the discussion in the section on MXene stability to address the points raised. We have chosen to retain the outlook-style format of this section, as it is intended to provide a forward-looking perspective on this emerging topic. Given that many aspects of MXene stability remain under active investigation, we believe this format appropriately reflects the evolving nature of the field and highlights the need for continued, collective efforts from the broader MXene research community.

*(Manuscript, Page 38-39)*

In practical device applications, MXene-based sensors are particularly vulnerable to harsh environmental conditions such as human sweat, body heat, and friction-induced mechanical stress.[81] Sweat, which contains water, salts, and various biomolecules, creates an electrolyte-rich environment that promotes the electrochemical oxidation of MXenes. Elevated temperatures from body-heat further accelerate this degradation process. As oxidation progresses, surface oxides form, reducing the electrical conductivity and sensing capabilities of the material.

Mechanical stress from continuous movement, bending, and skin contact introduces shear forces that can lead to microcracks, delamination, or abrasion of protective coatings. These mechanical damages expose fresh MXene surfaces to ambient oxygen and moisture, which are highly reactive and prone to rapid oxidation. This results in a recurring degradation cycle. The

combined effects of chemical exposure from sweat and mechanical wear are well-established contributors to the accelerated deterioration of MXene-based sensors,[82] ultimately leading to reduced signal stability, increased noise, and diminished sensitivity and durability, thus limiting the long-term usability of wearable devices.

To enhance MXene stability, surface passivation and protective coatings such as polymers, self-assembled monolayers, or inorganic layers, are commonly employed. While these approaches have shown short-term effectiveness, their long-term performance under real-world conditions remains uncertain due to a lack of extended experimental data.[83]. Over time, passivation layers can degrade through mechanical abrasion, delamination, or the infiltration of oxygen and water molecules via microscopic defects or diffusion pathways. Once compromised, these layers expose the underlying MXene, restarting the degradation process.

Therefore, ensuring long-term reliability of MXene-based sensors requires further research into robust encapsulation strategies and implementation of realistic aging protocols. These efforts are essential to fully understand and address the time-dependent failure mechanisms of passivated MXene-based sensors in practical environments.

**Reviewer #3:** The current review article presents an overview of the challenges and opportunities in the development of MXene-based sensors. While numerous review articles have already been published on the potential applications of MXenes, this manuscript distinguishes itself by placing greater emphasis on the challenges associated with their practical implementation. Overall, the manuscript is well-written and logically structured, with appropriate division into sections and subsections. The quality of the figures and the language used is commendable. However, the following points should be carefully considered before moving to the next stage of the review process:

1. Although the manuscript is intended to highlight the challenges, much of the focus is still on the potential applications of MXene-based sensors. In particular, the issue of long-term stability — a critical factor hindering real-world applications — requires greater emphasis. While the section "Addressing MXene stability issues" touches on strategies such as passivation layers and coatings, the descriptions are relatively brief. The authors are encouraged to expand this section with more in-depth discussion, supported by literature evidence, on methods to improve the long-term stability of MXenes in sensor applications.

Response:

We sincerely thank the reviewer for raising this important point. We fully agree that long-term stability remains a critical challenge for MXene-based sensors. In response, we have expanded the section titled "Addressing MXene Stability Issues" to provide a more in-depth discussion of current stabilization strategies, supported by recent literature. Following Reviewer #2's earlier recommendation, we have included a summary table highlighting recent advances aimed at improving sensor stability. We have chosen to retain the outlook-style format of this section to offer a forward-looking perspective on this rapidly evolving field. Given that many aspects of MXene remain under active investigation, we believe this approach effectively

reflects the dynamic nature of ongoing research and underscores the need for continued, collaborative efforts within the MXene community.

(Manuscript, Page 38-39)

In practical device applications, MXene-based sensors are particularly vulnerable to harsh environmental conditions such as human sweat, body heat, and friction-induced mechanical stress.[81] Sweat, which contains water, salts, and various biomolecules, creates an electrolyte-rich environment that promotes the electrochemical oxidation of MXenes. Elevated temperatures from body-heat further accelerate this degradation process. As oxidation progresses, surface oxides form, reducing the electrical conductivity and sensing capabilities of the material.

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Therefore, ensuring long-term reliability of MXene-based sensors requires further research into robust encapsulation strategies and implementation of realistic aging protocols. These efforts are essential to fully understand and address the time-dependent failure mechanisms of passivated MXene-based sensors in practical environments.

2. Scalability is another significant limitation in the practical deployment of MXene-based sensors. The authors are advised to elaborate on the challenges associated with large-scale synthesis and integration, and to discuss potential solutions or advancements in this area.

Response:

We have expanded several relevant sections and included recent advancements and strategies aimed at enabling large-scale fabrication of MXene-based sensors.

*(Manuscript, Pages 37-38)*

*Cost-effective, scalable and sustainable production of MXenes*

To make MXene-based sensors commercially viable, production must become more cost-effective and scalable without compromising performance. However, producing high-quality MXenes with consistent structural, chemical, and electrical properties at scale remains technically challenging and resource intensive. Conventional methods, such as selective etching using hydrofluoric acid or in-situ HF generation, rely on hazardous chemicals, require precise reaction control, and generate significant chemical waste. These issues raise safety, environmental, and cost concerns.

To overcome these limitations, research is shifting toward more sustainable and economical strategies. One promising approach involves repurposing carbon-rich industrial byproducts or biomass to produce MAX phase precursors.[251] This approach not only reduces raw material costs but also aligns with circular economy goals by turning waste into valuable feedstock. At the same time, synthesis techniques are being optimized for large-scale production. Chemical vapor deposition (CVD), particularly with titanium tetrachloride ($TiCl_4$), a low-cost byproduct of titanium manufacturing, offers a scalable, cleaner alternative to etching. CVD enables the direct synthesis of Cl-terminated MXenes, which show greater structural stability and oxidation resistance than conventional –OH, –O, or –F terminated MXenes from wet-etching methods.[252]

Vapor-phase growth methods like CVD offer enhanced control over film thickness, crystallinity, and uniformity, which are parameters critical for device integration and reproducibility. CVD allows for precise engineer of surface terminations, opening new opportunities for tailoring MXene properties for specific sensing applications.

Life cycle assessments (LCAs) further support the need for synthesis optimization, Recent studies highlight that electricity consumption during production is a major contributor to environment impact.[253] By simplifying synthesis, eliminating hazardous chemicals, and integrating process cost analysis, the overall sustainability and scalability of MXene production can be significantly improved.

As demand grows for flexible and wearable electronics, adopting scalable and environmentally sustainable methods like CVD becomes increasingly important. When combined with the use of industrial waste streams and streamlined synthesis protocols, these strategies represent a key step toward realizing the large-scale, reliable manufacturing of MXene-based sensors and devices.

*(Manuscript, Pages 39-40)*

*Large-scale integration and real-world testing*

Integrating MXenes into devices while retaining their unique properties remains challenging. Key obstacles include achieving uniformity, ensuring compatibility with diverse substrates, and enabling scalable, efficient fabrication.[87] Despite notable progress, most studies remains confined to controlled laboratory environments that do not reflect real-world conditions.

To move MXene-based sensors toward commercial use, rigorous testing under diverse environmental conditions is essential. Scalability will depend on standardized protocols for material selection, device fabrication, and performance metrics like sensitivity, response time, and detection limits. Long-term reliability, mechanical durability, calibration consistency, and quality control are also critical to ensure manufacturability ad rea-world functionality.

Start-ups will play a key role in bridging the gap between research and commercialization. Their agility allows them to focus on targeted applications, refine production methods, and respond quickly to market demands. By fostering innovation across cross-sector collaboration, start-ups can accelerate product development and reduce the risks associated with early-stage technology.

This is particularly valuable in fast-moving fields of wearable electronics and smart systems, where user needs and supply chains are still evolving. With growing investment and interdisciplinary cooperation, start-ups are poised to drive the adoption of MXene-based sensors in next generation intelligent and flexible technologies.

3. While artificial intelligence (AI) is mentioned as a potential solution, it should be noted that without reliable and stable sensor systems, the quality of training datasets will be compromised. This would, in turn, hinder the effectiveness of AI models in real-world applications. The manuscript should reflect on this interdependency more clearly.

Response:

We appreciate this insightful comment and have revised the section on AI to incorporate the suggestion.

*(Manuscript, Pages 41)*

The rapid advancement of artificial intelligence (AI) holds strong potential to enhance MXene-based sensors by improving their design, optimization, and performance. AI can help refine fabrication parameters, such as material density, surface uniformity, and electrode placement, ensuring consistency and preserving signal integrity. AI-driven modelling also enables deeper analysis of complex component interactions, supporting more efficient and cost-effective sensor development. Furthermore, AI's ability to process large datasets can reveal hidden patterns and anomalies during fabrication and testing, enabling continuous, real-time monitoring and personalized, responsive sensing.

However, the effectiveness of AI models depends heavily on the quality of sensor data. Unstable or inconsistent MXene sensors can produce noisy or incomplete data, compromising AI training and leading to models that perform poorly in real-world conditions. This reduces the accuracy, robustness, and applicability of AI-enhanced solutions. Therefore, developing reliable and reproducible MXene sensors is essential for successful AI integration. Without this foundation, the advantages AI offers in scalability, and application-specific performance will be limited, reinforcing the need for continued focus on sensor stability and durability.

4. Please consider adding a brief statement in the abstract to highlight the major challenges of MXene-based sensors, in order to align the summary with the main focus of the review.

Response:

The abstract has been revised to briefly highlight the major challenges.

*(Manuscript, Page 1)*

MXenes, a new class of two-dimensional transition metal carbides and nitrides, have gained significant attention for their exceptional physicochemical properties, making them promsing materials for diverse sensing applications. These include gas sensors for environmental monitoring, biosensors for diagnostics, strain sensors for wearables, and optical sensors for detecting light or chemical changes. Their unique conductivity, surface reactivity, optoelectronic behavior, and thermal stability enable broad technological versatility. Despite progress, key challenges such as material limitations, processing difficulties, limited real-world testing, and lack of scalable manufacturing, still hinder commercial adoption. Addressing these issues requires innovative design, fabrication, and evaluation strategies. This review summarizes recent advances in MXene-based sensors, examines existing barriers, and outlines pathways toward cost-effective, high-performance sensors for soft electronics. It aims to guide future development and inspire further innovation in the field.