MXene-based Bio-scaffold for Continuous Monitoring of Skin Regeneration

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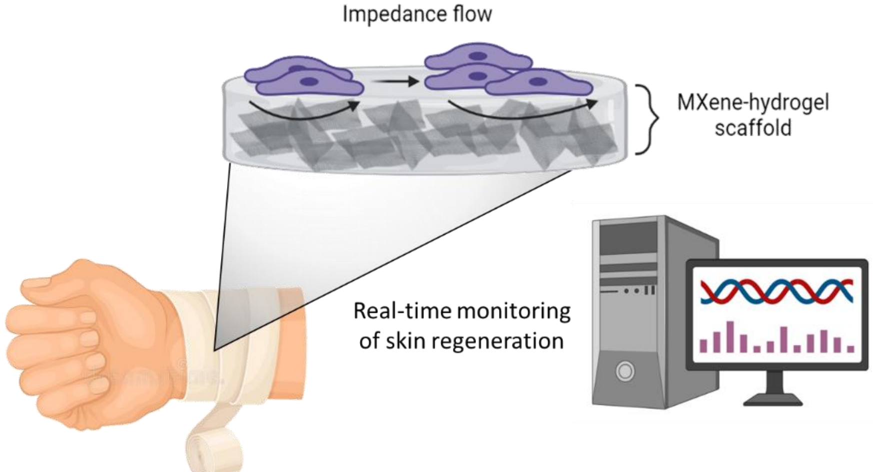
Abstract

Burns are a global public health problem, estimated to account for 180,000 deaths every year. Burn wounds are characterized by the destruction of skin structure and functionality and the loss of skin regeneration ability. To date, no satisfactory coverage materials exist to promote rapid and appropriate healing of burn wounds. Furthermore, there is currently no real-time monitoring of skin regeneration after implantation. The proposed study aims to develop a MXene-based bio-scaffold to serve as a smart wound dressing for continuous monitoring of skin regeneration. Integration of MXene nanosheets in the scaffold could improve the regeneration ability and regulate cellular behavior, including adhesion, growth, and regeneration of the damaged tissue. Our MXene-based bio-scaffold is envisioned to serve as a smart tissue that will allow to assess wound healing and regulate tissue function. It will provide unique information that will allow us to optimize our system. This novel approach of a 3D-engineered, nanostructure-based, electrically-active skin substitute will provide real-time monitoring of the tissue regeneration process, thus improving both quality of life and patient functionality. The strength of this work is the combination of unique technologies to simultaneously promote tissue regeneration and monitor the healing process.



Schematic illustration of the MXene-based bio-scaffold for continuous monitoring of skin regeneration

1. Scientific background

Burn wounds are characterized by the destruction of skin structure, functionality and, more importantly, the loss of skin regeneration ability. Today, the gold standard for the treatment of burn wounds is autologous skin grafts taken from healthy donor sites of the same patient. In cases of massive burn injuries, the extensive wounds limit the availability of donor skin, requiring the use of time-consuming skin expansion techniques to cover large areas. Moreover, harvesting autologous skin is invasive and creates a new wound in a healthy skin area, increasing patient morbidity and raising the need for an alternative treatment approach. Another significant challenge in such procedures is monitoring the healing process in terms of cell proliferation, inflammation, etc., while the implanted skin is inevitably inaccessible under wound dressing. A promising approach for such monitoring is impedance measurements, which can be used for reliable real-time monitoring of cell adhesion, morphology, proliferation rate and wound-healing *in vitro*[1,2].

Self-assembled peptide-based nanomaterials have exhibited potential for diverse application in fields such as tissue engineering, biosensors, materials science, nanodevices, biomedicine, energy storage, and others[3]. In particular, their relatively facile synthesis, bioinspired structure, tunable physical properties, intrinsic biocompatibility, and ease of functionalization provide short peptide-based self-assembled hydrogels with promising potential for bio-related applications[4]. The ability to self-assemble into fibrillar networks and three-dimensional (3D) hydrogels, mimicking the extracellular matrix (ECM), can facilitate the development of novel tissue regeneration biomaterials[5]. Despite many advantages, peptide-based hydrogels are not conductive, hindering their utilization for monitoring tissue regeneration processes.

MXene are a new group of 2D layered nanomaterials with a chemical composition of $M_{n+1}X_nT_z$, where M represents a transition metal, X represents carbon (C) and/or nitrogen (N), T represents surface functional groups (such as –O, –OH, or –F), and n is an integer[6,7]. These materials exhibit distinct properties, including high electrical conductivity, active surfaces, a large specific surface area, and good hydrophilicity. MXenes have been used for various applications, including sensing, electromagnetic shielding, ceramic nanocomposites, and energy storage[8]. Recently, MXene-based hydrogels have emerged as a new class of biomaterials for tissue engineering. By incorporating MXene nanosheets into hydrogel systems, the conductivity and mechanical properties of the hydrogel can be greatly enhanced[9]. Additionally, MXene nanosheets can be functionalized with bioactive peptides to promote cellular adhesion and proliferation[10]. One of the main advantages of MXene-based hydrogels is their ability to act as "smart" materials, capable of monitoring and responding to changes in the local environment. For example, MXene-based hydrogels can be used as sensors to detect changes in pH, temperature, or mechanical stress. They can also be used as actuators to release drugs or other bioactive molecules in response to specific stimuli[11]. MXene-based hydrogels have also been shown to have excellent biocompatibility, making them suitable for a wide range of biomedical applications, including wound healing, tissue regeneration, and drug delivery.

2. Project goal and impact

Burns are the most severe case of multi-trauma, requiring ICU support and the longest hospitalization period and accounting for 180,000 deaths worldwide each year[12]. Patients with burn injuries are prone to clinically related complications, including pneumonia, urinary tract infection, cellulitis, respiratory failure, and wound infection. Early surgical intervention directly influences the survival rate, hospitalization time and the overall clinical outcome. However, autologous skin implants require a healthy donor site, which is scarce in cases of extensive burns, and may result in donor site morbidity. Cell expansion techniques aimed to address these issues require significant time, leading to delayed treatment and healing. Moreover, currently available treatments do not allow monitoring of the healing process.

The multidisciplinary proposed project aims to ***develop a MXene-based composite hydrogel which will serve both for tissue regeneration of burn injuries and for real-time monitoring of the healing process***. The composite hydrogel will be designed to display adequate mechanical and structural properties to support cell growth, function as a reliable impedance sensor for cell monitoring. This bio-convergence project combining a cell-supporting scaffold and a cell growth sensor will constitute a significant advancement towards more efficient and controllable treatment of a major health risk.

3. Description of collaboration

The proposed project is part of an ongoing interdisciplinary collaboration between the Adler-Abramovich and Sokol research groups at Tel-Aviv University. Prof. Lihi Adler-Abramovich is the head of the Laboratory of Bioinspired Materials and Nanotechnology at the School of Dental Medicine, Faculty of Medicine, which focuses on mimicking self-assembly processes that occur in nature to develop novel biomaterials for various biological and medical applications, such as the design and synthesis of 3D hydrogel scaffolds for tissue regenaration[13–15]. Dr. Maxim Sokol is the head of the Advanced Ceramics Laboratory at the Department of Materials Science and Engineering, Faculty of Engineering, which focuses on the processing of advanced ceramics and ceramic composite materials, including ternary carbides and nitrides (MAX phases), and their exfoliation into 2D materials (MXenes). The lab explores novel MXene synthesis and fabrication techniques aiming at understanding the relationship between their functional properties and functional characteristics at various length scales.[16,17]

In the framework of the ongoing collaboration between the groups, we could fabricate a MXene-based composite hydrogel showing notable mechanical, electrical and self-healing properties that was utilized as a piezoresistive sensor (see Preliminary data below). Importantly, these advances, as well as the suggested project, cannot be achieved by either one of the partners alone and can only be accomplished through a collaborative effort.

4. Research plan

In order to achieve our goal and develop a novel MXene-based bio-scaffold for continuous monitoring of skin regeneration, we will pursue the following specific aims:

Aim 1. Optimization of the MXene-peptide composite hydrogel.

1.1 MXene synthesis. Biocompatible 2D $Ti_3C_2T_z$ MXene nanosheets will be synthesized and dispersed in an aqueous solution based on a previously described protocol[18]. Briefly, the Ti_3AlC_2 powders will be synthesized by mixing titanium carbide, aluminum, and titanium powders at a molar ratio of 2:1.15:1, respectively. After mixing, the powders will be heat-treated at 1450 °C under a protective atmosphere. The resulting partially sintered block will be ground to fine powders and filtered through a 400 mesh (< 38 µm) sieve to produce particles of ~10-30 µm. Next, the Ti_3AlC_2 powder will be etched in an HCl and LiF solution for 24 h at 35 °C. For decantation of the acidic supernatant, the slurry will be washed several times using type I deionized (DI) water until the pH of the solution reaches >6. At this point, DI water will be added to the resulting $Ti_3C_2T_z$ "clay", and the mixture will be sonicated and centrifuged. Finally, the supernatant will be pipetted off and sealed under Ar for storage before use.

1.2 Design and fabrication of MXene-based bio-scaffolds using short peptides. The design and construction of the MXene-based bio-scaffold will be performed by the solvent-switch method[19] using short peptides, such as fluorenylmethoxycarbonyl-diphenylalanine (Fmoc-FF), which self-assemble into fibrillar networks and 3D hydrogels, mimicking the structural characteristics of the ECM[20,21]. We will also use vacuum filtration to fabricate a free-standing 3D film[22]. Since modification of the peptide sequence may alter the properties of the assembly, we will study the effects of the addition of positively- and negatively-charged amino acids, namely Lysine (K) and Aspartic acid (D), respectively, on the assembly of the peptides with the MXene nanosheets and the properties of the resulting hydrogels. We will further study the incorporation of Fmoc-phenylalanine-arginine-glycine-aspartic acid (Fmoc-FRGD), harnessing the RGD motif to support cell attachment based on molecular recognition[14,23].

1.3 Characterization of the MXene-hydrogel scaffold.

1.3.1 Morphological characterization of the MXene-based hydrogel using high resolution scanning electron microscopy (HR-SEM) and transmission electron microscopy (TEM). Characterization of the produced scaffolds will be performed using HR-SEM and TEM. The single fiber and MXene nanosheet morphology, distribution of the MXene nanosheets in the fibrillary matrix, and layered structure of the MXene/peptide film will be examined and compared. All these physical parameters have been identified as significant for bio-sensing abilities and for the penetration and proliferation of cells on fibrous scaffolds.

1.3.2 Interfacial interactions of the MXene-hydrogel. To gain insight into the interactions between the MXene nanosheets and the peptides, the interfacial interactions in the MXene/peptide composite hydrogel will be examined using X-ray photoelectron spectroscopy (XPS). The interfacial interactions will provide guidance for the design and optimization of the composite MXene/peptide hydrogel scaffold[24].

1.3.3 Mechanical properties of the MXene-hydrogel scaffold. The mechanical properties of the composite MXene/peptide hydrogel will be examined by rheological analysis. First, strain sweep experiments will be carried out to determine the linear viscoelastic regime. Then, the storage and loss modulus (G' and G'' respectively) of the MXene/peptide hydrogels will be examined by a dynamic frequency sweep experiment. Temperature sweep experiments will be carried out on the MXene/peptide hydrogels to examine their stability at physiologically relevant temperatures[25].

Aim 2. Development of the MXene-based bio-scaffold as a cellular impedance sensor for real-time cell proliferation analysis.

2.1 Cellular impedance sensor fabrication and development. We will fabricate a cellular impedance sensor by measuring the electrical properties of cells, including their resistance and capacitance. These properties will provide information about the vitality and the location of the cells. The device will consist of a pair of electrodes placed in contact with the cells, and an electrical current will pass through the cells to measure their impedance. The MXene/hydrogel consists of conductive 2D nanosheets of MXene embedded within a fibrillary 3D matrix, forming a 3D nano array of electrodes. This arrangement enables populations of cells to be monitored simultaneously and thereby provides exquisite sensitivity to detect both the number of cells attached to the hydrogel scaffold and the size/morphology of the cells.

2.2 Sensing performance of the MXene hydrogel scaffold. The electrical performance of the MXene-hydrogel will be analyzed using current−voltage (I−V) conductivity curves on a Keithley 2614B source-meter using the two-probe method. The samples will be drop-cast on prefabricated field-effect transistor substrates (Ossila, U.K.) with an electrode gap of 2 μm and dried under ambient conditions. Conductance values will be extracted from the slope of the linear curves.

2.3 Sensing frequency, sensitivity, and durability of the MXene-hydrogel scaffold. The frequency, sensitivity and durability of the impedance sensor will be evaluated using a custom-made measurement system based on electrical cell-substrate impedance sensing (ECIS) system described by Giaever and Keeseon[26].

Aim 3. Cell culture analysis and real-time monitoring of the MXene-based bio-scaffold

3.1 Biocompatibility and cells morphological analysis. The scaffold's biocompatibility will be assessed *in vitro* using a 3T3 fibroblast cell line. A cell viability assay will be performed on the MXene-hydrogel scaffold by colorimetric assays allowing to assess the cellular metabolic activity, including Alamar blue, and XTT (2,3-bis-(2-methoxy-4-nitro-5-sulfophenyl)-2H-tetrazolium-5-carboxanilide). In addition, Qualitative assessment of cell viability when grown on the MXene-hydrogel scaffold will be performed using a Live/Dead staining. Live/Dead staining solution containing fluorescein diacetate (6.6 μg/mL) and propidium iodide (5 μg/mL) will be used to label the live and dead cells in green and red, respectively. The cells will be immediately imaged using a Leica SP8 X confocal microscope.

3.2 Cells growth analysis and real-time monitoring on the scaffold. The cellular impedance will be analyzed *in vitro* using 3T3 fibroblast cell line cultured on top of the MXene-hydrogel scaffold. The MXene-hydrogel will serve a dual role: (1) a scaffold for cell attachment and skin regeneration; (2) a nanoelectrode array to monitor the regeneration process. The sensor output will be calibrated and compared to standard cell viability analysis methods described in section 3.1.

5. Preliminary data

The self-assembly of the composite MXene-based bio-scaffold into a 3D hydrogel was triggered using the solvent-switch method. The peptide monomers were dissolved in dimethyl sulfoxide (DMSO) to form a stock solution, which was then diluted into the colloidal suspension of the MXene to trigger the self-assembly. Figure 1 schematically illustrates the formation of the MXene-based bio-scaffold composite hydrogel.

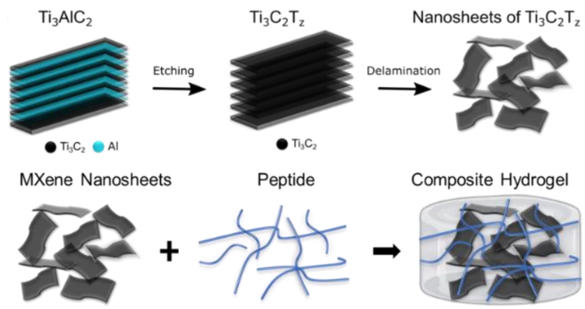


Figure 1. Schematic illustration of the MXene-based bio-scaffold composite hydrogel fabrication.

Aiming to demonstrate the cytocompatibility of the MXene-based hydrogel, 3T3 fibroblasts were seeded on top of the scaffold. Phalloidin staining indicated proper cell morphology and viability of the cells grown on the MXene-based hydrogel, comparable to the control (Figure 2).

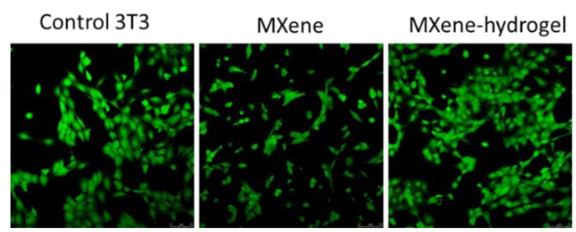


Figure 2. 3T3 fibroblast cells grown on non-coated plate (left), MXene alone (middle), and MXene-based bio-scaffold composite hydrogel (right).

To understand the influence of the MXene concentration on the conductivity of the composite hydrogel, three formulations of MXene-peptide composite hydrogels were prepared with variable concentrations of the MXene nanosheets (0.3%, 0.15%, and 0.05% (w/v)), while maintaining a peptide concentration of 1% (w/v). The conductivity of the MXene-based hydrogel was found to increase with the increase in MXene concentration (Figure 3a). Next, we aimed to demonstrate the use of the MXene-based composite hydrogel as a piezoresistive sensor under dynamic and static conditions. The I–V curve showed a clear linear relationship to an increase in the applied force, indicating that the pressure-sensing response of the hydrogel was stable under different external pressures (Figure 3b). The sensitivity of the MXene-based piezoresistive sensor was 38.5, 3.5, and 0.25 kPa, in the low-, medium-, and high-pressure range, respectively, superior to previously-reported MXene-based piezoresistive sensors[22,27–30].

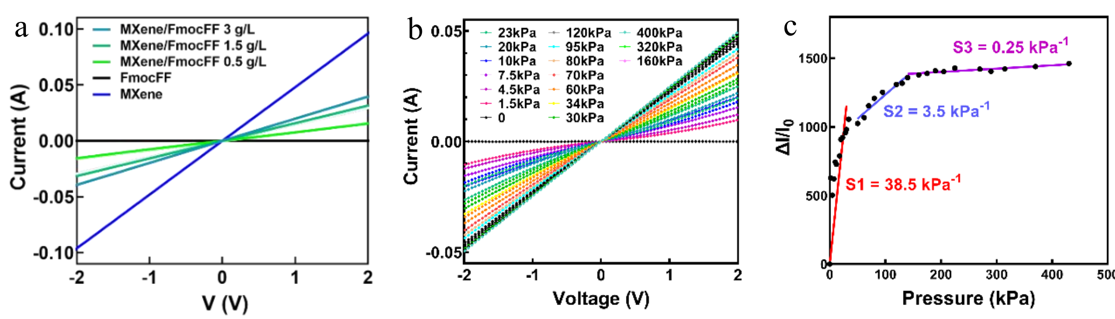


Figure 3. a) I−V characteristic curves of the MXene/Fmoc-FF composite hydrogel with different MXene concentrations. b) I-V curves of the piezoresistive sensor under different pressures ranging from 0-400 kPa. c) The sensitivity curve of the piezoresistive sensor is divided into 3 areas: S1 (0-34 kPa), S2 (50-190 kPa), and S3 (190-400 kPa).

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Curriculum vitae

PERSONAL INFORMATION

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EDUCATION

2010	Ph.D., Faculty of Life Sciences, Tel Aviv University. Supervisor: Prof. Ehud Gazit
2006	M.Sc., (Summa cum laude), Biotechnology, Faculty of Life Sciences, Tel Aviv University.
2004	B.Sc., (Magna cum laude). Life Sciences, Faculty of Life Sciences, Tel Aviv University.

POSITIONS AND EMPLOYMENT

2020 – Present	Associate Professor, Faculty Member, Department of Oral Biology, The Goldschleger School of Dental Medicine Sackler Faculty of Medicine, Tel Aviv University, Israel
2015 – Present	Affiliated, Tel Aviv University Center for Nanoscience and Nanotechnology, Tel Aviv University, Israel.
2015 – 2019	Assistant Professor, Faculty Member, Department of Oral Biology, The Goldschleger School of Dental Medicine Sackler Faculty of Medicine, Tel Aviv University, Israel
2011 – 2015	Research Associate, Department of Molecular Microbiology and Biotechnology, Tel Aviv University.
2010 – 2011	Postdoctoral Fellow, Department of Molecular Microbiology and Biotechnology, Tel Aviv University. Supervisor: Prof. Ehud Gazit

AWARDS AND SCHOLARSHIPS (Selected)

2022	Dean Excellent Teacher Award for 2022, Sackler Faculty of Medicine
2022	Sackler Faculty of Medicine, Best Publication Award 2021
2022	Nanomaterials 2021 Best Paper Award
2020	Awarded the ERC-Starting Grant
2018	Sackler Faculty of Medicine, Excellence Publication Award
2017	UK-Israel SYNERGY Programme

ACTIVE RESEARCH GRANTS (Selected)

2023-2025	Enzyme encapsulation in peptide-based nanostructures for fungal mycotoxin reduction. **Ministry of Agriculture**. (125,000 €)
2023-2025	In vitro 3D cell models of healthy and OSTEOpathological aging bone tissue for implantation and drug testing in a multidisciplinary NETwork (Osteonet). Marie Skłodowska-Curie Research and Innovation Staff Exchange Consortium, **European Commission**. (110,000 €)
2022-2025	Refining the efficacy of systemic administration of bioactive molecules for Parkinson's Disease **M-ERA.NET**, (55,000 €)
2021-2025	PersonalBone-Multifunctional Personalized Self-Assembled Biomaterials for Bone Regeneration-**European Research Council (ERC),** (1,500,000 €)
2021-2024	Bio-Active Printed Implants for Bone Regeneration Following Tumor Resection. **Ministry of Science Technology and Space**. (110,000 €)
2020-2023	The Mechanosensing Effect on Space Flight Osteopenia: Developing a Microgravity Organoid Model. Space Program, **Ministry of Science Technology and Space**. (140,000 €)

INSTITUTIONAL RESPONSIBILITIES

2021-2022	Ad Hoc Academic appointment committee, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University
2020-date	Head, Grants Committee, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University
2020-date	Steering Committee, Metabolic Medicine Davison, BLAVATNIK CENTER for Drug

	Discovery, Tel Aviv University
2020-date	Research Committee, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University
2020-date	Scientific committee, ADAMA Center for Novel Delivery Systems in Crop Protection, Tel Aviv University
2019-date	Head, Academic Committee, Interdepartmental Core Facilities at the Faculty of Medicine
2019-date	Co-director, Bioengineering Materials, Cells and Tissues Hub, BioMed@TAU
2019-date	Scientific Committee, Center for Nanoscience and Nanotechnology, Tel Aviv University.
2016-date	Evaluator of DMD theses, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University
2016-2017	Ad Hoc Academic appointment committee, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University
2016-2020	DMD admission committees, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University
2016-2018	Young Researcher Grants committee, School of Dental Medicine, Sackler Faculty of Medicine, Tel Aviv University

COMMISSIONS OF TRUST

2018-date	PLOS ONE Editorial Board
2016-date	Evaluator of grant proposals including Israel Science Foundation (ISF), US-Israel Binational Science Foundation (BSF), Ministry of Science, Technology, and Space (MOST)
2016-date	External Examiner of Research Theses including research Ph.D. thesis (Viva Voce Examination), University of Cambridge, UK; Ph.D. thesis the University of Naples “Federico II” Department of Pharmacy; Ph.D. thesis School of Chemistry, TAU; Ph.D. theses, Ben-Gurion University; Ph.D. theses, Technion; M.Sc. thesis, Department of Material Science and Engineering, TAU.
2011-date	Reviewer for several journals, including *Angewandte Chemie*, *ACS Biomaterials Science & Engineering*, *Analytical Chemistry*, *Scientific Reports*, *Chemistry - A European Journal*, *Israel Journal of Chemistry*, *and Lab on a Chip*.
2017, 2018	Reviewer for Best Poster Prize competition, Nanoscience and Nanotechnology Workshop, Current Challenges in Amyloid Diseases.

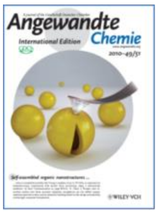
OUTREACH

Invited speaker, Engineering Women's Forum "WomEng" as a part of "HerWay" lecture series, Mentoringprogram to help young women make career choices in science, Faculty of Medicine, Tel Aviv University, Hosting QueenB Association for the advancement of female representation in technology and science, Mentoring, ALPHA program for gifted young scientists in TAU

PATENTS

Link to Issued US Patents on Patent Public Search Basic

SCIENTIFIC PUBLICATIONS (Google Scholar H-index=43), 105 publications, including 12 covers



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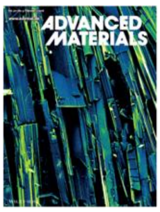
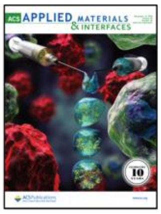
Nature Chem. Biol. 2012

Chem. Soc. Rev. 2014

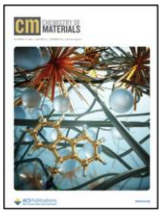


ACS Appl. Mater. Interfaces 2018

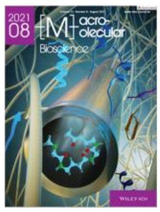


ACS Appl. Mater. Interfaces 2018

Isr. J. Chem 2020



Chem. Mater. 2020



Macromol. Biosci. 2021

List of Published Work in MyBibliography:
https://www.ncbi.nlm.nih.gov/pubmed/?term=adler-abramovich
Complete List of Published Work in Google Scholar:
https://scholar.google.co.il/citations?user=BN4LwRAAAAAJ&hl=en

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EDUCATION:

2014-2017	Ph.D., Ben-Gurion University of the Negev – Materials Engineering
2012-2014	M.Sc., Ben-Gurion University of the Negev – Materials Engineering
2008-2012	B.Sc., Ben-Gurion University of the Negev – Physics
2008-2012	B.Sc., Ben-Gurion University of the Negev – Materials Engineering

POSITIONS & EMPLOYMENTS:

2020-present	Senior Lecturer (Assistant Professor), tenure track Department of Materials Science and Engineering Tel-Aviv University, ISRAEL
2018-2020	Postdoctoral Researcher Department of Materials Science and Engineering, Drexel University, Philadelphia, PA, USA

AWARDS & FELLOWSHIPS (selected):

2019-2020	The Louis and Bessie Stein Family Fellowship Drexel University, Philadelphia, PA (USA)
2014-2018	Negev-Tzin Ph.D. Fellowship Kreitman School of Advanced Graduate Studies, Ben-Gurion University of the Negev, Beer-Sheva, Israel
2014	Dean's award for excellence in M.Sc. studies, Faculty of Engineering, Ben Gurion University of the Negev, Beer-Sheva, Israel

PROFESSIONAL ACTIVITIES (selected):

- **Guest Editor,** Special Issue "Spark Plasma Sintering", *Journal of Manufacturing and Materials Processing*
- **Evaluator of Grant Proposals**
  PAZY Foundation, US-Israel Binational Science Foundation (BSF), Ministry of Science and Space (MOST), National Science Centre Poland (OSF)
- **Ad-hoc Reviewer**
  Scripta Materialia, Journal of the European Ceramic Society, Journal of the American Ceramic Society, Journal of Alloys and Compounds, Journal of Advanced Ceramics, Ceramics International, Materials Science and Engineering A, Materials Research Letters
- **Membership in professional/scientific societies**
  Since 2015 American Ceramic Society
  Since 2014 Materials Research Society (MRS)
  Since 2014 Israel Vacuum Society (IVS)

ACTIVE RESEARCH GRANTS (selected):

2023-2025	MAX phases for high temperatures applications, **Israel Ministry of Defense - Maf'at.** (130,000 €)
2022-2025	Advanced Ceramics and Powder Metallurgy Laboratory, **Israel Science Foundation (ISF).** (320,000 €)
2022-2023	Energetic composite materials based on MAX phases**, Israel Ministry of Defense - Maf'at.** (65,000 €)
2021-2026	MXene Based Energy Materials Guided by 3D Atomic Resolution Tomography, **German Federal Ministry of Education and Research (BMBF).** (1,600,000 €)

SCIENTIFIC PUBLICATIONS (selected):

1. A. Hazan, B. Ratzker, D. Zhang, A. Katiyi, M. Sokol, Y. Gogotsi and A. Karabchevsky, "MXene Nanoflakes Enabled All-Optical Nonlinear Activation Function for On-Chip Photonic Deep Neural Networks", *Advanced Materials*, ACCEPTED (2023) [DOI]

2. B. Ratzker, O. Messer, B. Favelukis, S. Kalabukhov, N. Maman, V. Ezersky, M.Sokol, "MXene-Based Ceramic Nanocomposites Enabled by Pressure-Assisted Sintering", *ASC Nano*, 17, 1, 157-167 (2023) [DOI]
   - **Highlighted on issue cover**

3. R. Pai, V. Natu, M. Sokol, M. Carey, T. Greszler, M.W.Barsoum and V. Kalra, "Sulfur confined MXene hosts enabling the use of carbonate-based electrolytes in alkali metal (Li/Na/K)-sulfur batteries", *Materials Today Energy*, 27 101000 (2022) [DOI]

4. B. Ratzker, A. Wagner, M. Sokol, L. Meshi, S. Kalabukhov and N. Frage, "Deformation in nanocrystalline ceramics: A microstructural study of $MgAl_2O_4$", *Acta Materialia*, 183 137-144 (2020) [DOI]

5. V. Natu, R. Pai, M. Sokol, M. Carey, V. Kalra and M.W. Barsoum, "2D $Ti_3C_2T_z$ MXene synthesized by water free etching of Ti_3AlC_2 in polar organic solvents", *Chem*, 6 616-630 (2020) [DOI]
   - **Highlighted on issue cover**

6. M. Sokol, S. Kalabukhov, E. Zaretsky and M.W. Barsoum, "Abnormal Response of Ti_3SiC_2 To High Strain-Rate Loading", *Physical Review Materials*, 3 063610-063621 (2019) [DOI]
   - **Selected as Editors' Suggestion**

7. V. Natu, J. L. Hart, M. Sokol, H. Chiang, M. L. Taheri and M.W. Barsoum, "Edge Capping of 2D-MXene Sheets with Polyanionic Salts to Mitigate Oxidation in Aqueous Colloidal Suspensions", *Angewandte Chemie*, 58 (2019) [DOI]
   - **Selected as Hot Paper**

8. S. Kota, M. Sokol and M.W. Barsoum, "A Progress Report on the MAB Phases: Atomically Laminated, Ternary Transition Metal Borides", *International Materials Reviews* (2019) [DOI]

9. M. Sokol, V. Natu, S. Kota, and M.W. Barsoum, "On the Chemical Diversity of the MAX Phases", *Trends in Chemistry*, 1 [2] 210-223 (2019) [DOI]

10. M. Sokol, B. Ratzker, S. Kalabukhov, M. P. Dariel, E. Galun and N. Frage, "Transparent Polycrystalline Magnesium Aluminate Spinel Fabricated by Spark Plasma Sintering*", Advanced Materials*, 30 1706283 (2018) [DOI]

8. Budget

PI	Category	Sum (k$)
Lihi Adler-Abramovich	Personnel – Ph.D. student fellowship	25
Lihi Adler-Abramovich	Personnel – M.Sc. student fellowship	10
Lihi Adler-Abramovich	Consumables, including peptides, chemicals and solvents	15
Maxim Sokol	Personnel – Postdoc/Ph.D. student fellowship	30
Maxim Sokol	Personnel – M.Sc. student fellowship	10
Maxim Sokol	Consumables, including chemicals and solvents for MAX and MXene synthesis	10
Total		100

9. Budget Justification

Personnel: In the proposed research, we plan to design a MXene-based composite hydrogel and test the structure, electrical performance, and biocompatibility of the fabricated scaffolds. In addition to the PIs, the proposed project will include post-doctoral fellows, Ph.D. and two M.Sc. students. A portion of their fellowships is included in the requested budget.

Consumables and materials: Funding is allocated for solvents, hydrogel building blocks, cell culture media, and other chemicals.

In-kind contribution of 25%: part of the projected fellowships will be covered by Tel Aviv University funds. Specifically, $12.5K of the personnel costs of the Adler-Abramovich lab will be covered by funds of the Faculty of Medicine, and $12.5K of the personnel costs of the Sokol lab will be covered by funds of the Faculty of Engineering.

●●● Office of the Dean

לשכת הדקן וראשת המנהל ●●●

The Iby and Aladar Fleischman Faculty of Engineering
Tel Aviv University

הפקולטה להנדסה
ע"ש איבי ואלדר פליישמן
אוניברסיטת תל אביב

January 5, 2023

Dear members of the Zimin Institute,

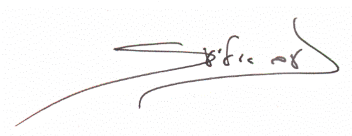
I am writing to wholeheartedly endorse the application of Dr. Sokol and Prof. Adler-Abramovich for a Zimin Institute grant. I have had the pleasure of working closely with both individuals and can confidently say that they are truly exceptional in their respective fields.

Prof. Adler-Abramovich has a strong track record of innovative discoveries in the field of bioinspired materials science. Dr. Sokol has a strong track of developing innovative solutions to complex problems, in particular in the area of 2D and 3D ceramics.

Their proposed project entitled" MXene-based bio-scaffold for continuous monitoring of skin regeneration" aligns perfectly with the mission of your organization and has the potential to make a significant impact on the field of bio-engineering and advance better lives. I wholeheartedly recommend them for your consideration and support.

Please do not hesitate to contact me if I can be of further help

Sincerely,



Professor Noam Eliaz

Dean

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מיסודה של אחוות אלפה אומגה הבינלאומית
Founded by **Alpha Omega International** Dental Fraternity

The Maurice and Gabriela Goldschleger School of Dental medicine
Sackler Faculty of Medicine
Tel Aviv University

בית הספר לרפואת שיניים ע"ש מוריס וגבריאלה גולדשלגר
הפקולטה לרפואה ע"ש סאקלר
אוניברסיטת תל אביב

29 January 2023

Dear members of the Zimin Institute,

I am writing to unequivocally endorse the application of Prof. Adler-Abramovich and Dr. Sokol for a Zimin Institute grant. Both researchers have highly impressive track record of successful research in their respective fields and I am confident that their ongoing collaboration will continue to lead to important achievements.

The proposed project entitled "MXene-based bio-scaffold for continuous monitoring of skin regeneration" is an interdisciplinary effort combining the expertise of two excellent researchers. The project aligns perfectly with the mission of the Zimin organization and has the potential to make a significant impact on the field of bio-engineering and advance better lives. I wholeheartedly recommend the project for your consideration and support.

Please do not hesitate to contact me if I can be of further help.

Sincerely,

Prof. Shlomo Matalon
Head of School

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