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EDITORIAL

The global expansion of MXenes

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Since their discovery in 2011 [1], the family of 2D transition metal carbides and nitrides, MXenes, has made remarkable progress. While their initial development was relatively slow compared to their current growth and some other 2D materials, MXenes have gained momentum over the past seven years. In the first three years of their existence (from 2011 to 2014), only about 50 publications from a dozen countries appeared and more than half of all MXene publications came from the USA. They included many discovery papers, which reported new MXene compositions, first property measurements, delamination and processing techniques, as well as potential applications [2–10]. The trend of discovering new MXene compositions and structures continued to be dominated by US researchers, with approximately 70% of all experimentally reported MXenes, while Asia and Europe contributed about a dozen new compositions [11]. One should also account for enabling discoveries that not just added a single new composition to the family, but opened new directions, such as the first nitride (Ti_4N_3) [12], new MXene subfamilies, such as in- and out-of-plane ordered structures [13, 14], M_5X_4 [15], high-entropy [16, 17], oxycarbides [18] and carbonitrides in $M_2(C,N)$ [19] and $M_4(C,N)_3$ [20] families. Most of those discoveries were made in the USA or resulted from international efforts involving US scientists. However, the overall research growth of MXenes has certainly been a global effort since 2012, and their development extends beyond the boundaries of any single country.

MXenes research has greatly expanded globally since 2015, with more publications than ever coming from outside of the USA, including many breakthrough papers [21]. To date, MXene research has been conducted by about 70,000 scientists from more than 7600 institutions from over one hundred countries across all six continents (Fig. 1). Considering that this figure is based on the data from the Web of Science, which has a high barrier for adding periodicals to the database, total numbers are expected to be 20–30% higher. With little interest from the US funding agencies and industry to support MXene research and development, countered by generous funding for the topic elsewhere, the center of gravity in both, fundamental science, and, especially, applied research and development shifted overseas. The total number of MXene publications from Asia now exceeds that of the USA by more than sevenfold highlighting the worldwide effort to develop and understand this family of 2D carbides and nitrides. Many MXene publications are intercontinental, sometimes involving groups from the USA, Asia, and Europe working on papers together to achieve and report significant fundamental breakthroughs in the field [21]. There have been many productive collaborations, despite the disruptions of the pandemic era and the worsening geopolitical situation in the world.

The quickly growing number of publications is important as research papers expand our knowledge base. However, patent filing has also seen a consistent increase in the past decade. As of a year ago, about 3200 unique patents/applications (from ~4000 total) were filed in China, followed by the USA with over 550 and Korea with about 120 unique patents or patent applications (based on PatSnap report, October 27, 2022). Due to the 18-month gap between patent filing and publishing by patent offices and considering that the number of filings exceeded 1100/year in 2021, one can expect well over 6000 patent applications filed by now. As of October 2022, 1559 were granted. More than 64% were from Chinese universities and research institutes, with

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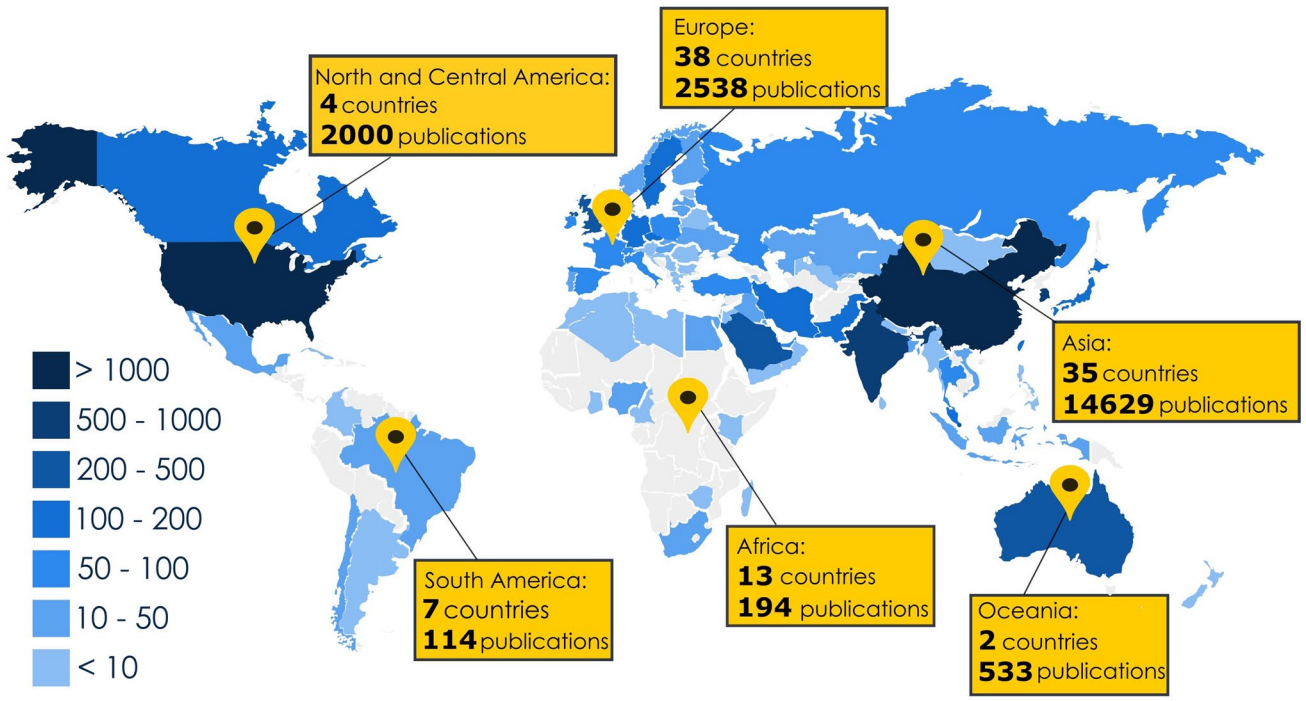

Fig. 1 The number of MXene publications and counties per continent based on the topic search on the word MXene on Web of Science on September 30, 2023 (courtesy of Magdalena Zywolko, Alex Inman and Jamie Banks, Drexel University)

18% coming from big corporations (Murata, LG, Samsung, Mitsubishi Materials, Nippon Steel, Intel, etc.), with Murata Manufacturing having the lead with about 30 patents granted and pending, as this Japanese company was the first one to license the synthesis and several important applications of MXenes from Drexel University. Two Chinese companies, Suzhou Beike Nano Tech and Foshan Shunde Sanbei Electronics, follow with over 20 patent applications each. Moreover, according to the year-old PatSnap analysis, China is the innovation hub with over 3000 priorities originating in China, with the USA being a distant second with about 150. Shouldn't it serve as a wake-up call for the USA and Europe?

Patent filings eventually lead to products. An increasing number of companies offer MXenes for research purposes using technology licensed from Drexel University (Sigma Aldrich, Carbon-Ukraine, Nuevogen, 2D Semiconductor, Nanoplexus, ACS Material, Japan Material Technologies, Ballydel Technologies, InnoMXene, etc.). There are more than 20 companies in China that sell MXenes online via Alibaba and other portals. The batch sizes reach 10 kg or more. This, along with patents filed by large corporations and small businesses alike, provides a clear indication of MXenes moving toward real-world industrial applications. The fact that *Graphene and 2D Materials* is an official journal of the MXene Association speaks for itself.

Annual international conferences dedicated to MXenes started in 2018, with the 1st International Conference on MXenes organized at Jilin University, serving as crucial platforms for productive discussions among researchers who are active in the field. Building on the success of MXene conferences over the past five years, there are plans for about ten MXene conferences and symposia in 2023–2024. Following three well-attended symposia at Materials Research Society (MRS) Meetings, the 2023 MRS Fall Meeting in Boston, MA, and the 2024 MRS Spring Meeting in Seattle, WA, will feature dedicated MXene symposia. The 3rd MXene Conference is scheduled for August 5–7, 2024, at Drexel University in Philadelphia, PA, the birthplace of MXenes. The 5th International Conference on MXenes is expected to take place in October 2024 in Xi'an, China. EUROMXENE is also scheduled for June 2024, in Valencia, as the first dedicated MXene conference in Europe. In addition, several symposia focusing on 2D materials, nanocomposites, carbide ceramics, etc., will include MXenes as one of their key areas of interest. These events include the American Chemical Society (ACS) 2024 Spring Meeting in New Orleans, LA, the American Ceramic Society (ACerS) Pan American Ceramics Congress and Ferroelectrics Meeting of Americas (PACC-FMAs) in Panama, and the ACerS International Conference and Expo on Advanced Ceramics and Composites (ICACC24) in Daytona Beach, FL. Furthermore, there are plans for a MXene symposium at the European Materials Research Society (E-MRS) conference in the fall of 2024. Of course, there are numerous MXene

sessions at many other conferences, especially graphene and 2D materials conferences worldwide.

The above discussion suggests that a large community of MXene researchers has been formed and we can expect accelerating progress as the critical mass of scientists and engineers focusing on MXenes is being accumulated. Still, since MXenes are developing into the largest known family of inorganic low-dimensional materials with an enormously broad range of applications in almost every engineering field, as well as healthcare and analytical chemistry, there is plenty of room for discovery for any number of researchers entering the field of these fascinating materials. Moreover, considering the transformational role that MXenes are expected to play in the fields from communication to optoelectronics, healthcare, energy and environment, countries that seize the opportunity earlier may gain a major technological advantage.

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