Sustainable Production of Two-Dimensional Crystals for Nanofiltration Membranes and Flexible Electronics

Sushmitha Veeralingam
Vicente Lopes, Pedro D. Silva, Andrea Capasso
International Iberian Nanotechnology Laboratory, 4715-330 Braga, Portugal
andrea.capasso@inl.int

Two-dimensional crystals (2DCs) offer significant opportunities for advancing technologies such as energy harvesting, optoelectronics, flexible electronics, and water purification, but large-scale production is constrained by fabrication routes that compromise scalability and environmental sustainability. Here, we present an integrated materials strategy for producing high-quality 2DCs using scalable and environmentally benign processes while maintaining control over crystal structure, dispersibility, and assembly into functional architectures. Hazardous solvents traditionally employed in liquid-phase exfoliation were replaced with greener alternatives, such as Cyrene, enabling efficient exfoliation and stable colloidal dispersions [1]. From these dispersions [2], we fabricated functional graphene- and MXene-based nanofiltration membranes with Å-scale interlayer spacing. These membranes exhibited selective ion transport, long-term aqueous stability without swelling, and intrinsic antibacterial activity [3,4]. In parallel, the graphene dispersions were formulated into sustainable, printable graphene pastes applicable in flexible micro-supercapacitors, sensors, and electromagnetic interference shielding coatings with high performance [5]. Extending these design principles, we developed all-carbon hybrid nanocarbon/elastomer inks and fabricated wearable strain and motion sensors with high gauge sensitivity, stability, and mechanical durability under repeated deformation [6]. Finally, we established water-based, scalable processing routes for producing high-quality 2D transition metal dichalcogenide dispersions. Using this approach, MoS_2 flakes were interfaced with GaN to form vertical heterojunctions with strong built-in electric fields for self-powered photodetection [7] and integrated into composite polymer architectures for piezo-triboelectric energy harvesting and motion sensing [8]. Overall, this work establishes a sustainable framework for environmentally responsible, high-throughput 2D crystal production, bridging materials processing to device integration across filtration, electronics, sensing, and optoelectronics.

References

[1] S.S. Nemala et al., Adv. Mater. Interfaces, 11 (2024), 2400203.
[2] S.S. Nemala et al., ACS Appl. Energy Mater., 1 (2018), 2512-2519.
[3] S.S. Nemala et al., Adv. Funct. Mater., 33 (2023), 2214889.
[4] B. Silva et al., J. Membr. Sci., (2026). doi:10.1016/j.memsci.2026.037673882600178X.
[5] S.S. Nemala et al., Nano Energy, 127 (2024), 109781.
[6] S.S. Nemala et al., Small (2025), e06844.
[7] S. Veeralingam, et al. ACS Photonics 1012 (2023), 4408-4416.
[8] S.B. Choi, et al., Nano Energy (2025), 111000.