

Table S1. Comparative cost benchmarking of MAX phase precursors for MXene synthesis based on commercial pricing and stoichiometric ratios (100 g basis).¹⁻³

Materials	Ratio	100 g/USD
Ti ₃ AlC ₂	Ti:Al:C ~ 3:1.2:1.8	420.23
Ti ₃ GaC ₂	Ti:Ga:C ~ 2.1:2.3:1.7	802.1
Ti ₄ AlN ₃	Ti:Al:N ~ 50:13.5:36.5	209.95
Ti ₅ Al ₂ C ₃	Ti:Al:C ~ 5:2.15:2.78	415.56
Ti ₂ InC	Ti:In:C ~ 2.1:2.3:1.7	944.62

Table S2. Semi-quantitative sustainability and industrial viability comparison.⁴⁻⁶

Parameter	HF Etching	MILD	Fluoride-Free	Halogen	Molten Salt
Reaction Temp	RT	RT	RT–80°C	RT	550–750°C
Energy Demand	Low	Low	Low–Moderate	Low	High
Hazard Level	Very High	High	Low–Moderate	Very High	Moderate
Waste Neutralization	Intensive	Moderate	Low	Intensive	Moderate
Chemical Cost	Low	Moderate	Moderate–High	High	Moderate
Process Complexity	Low	Low	Moderate	High	High
Estimated Industrial Scalability	Medium	High	Developing	Low	Promising

Table S3. Comparative overview of representative 2D materials: properties, strengths, and limitations

Material	Key Physicochemical Properties	Major Strengths	Main Limitations
MXenes ⁷⁻⁹	<ul style="list-style-type: none"> - High electrical conductivity ($\sim 10^3$–10^4 S·cm⁻¹), moderate thermal conductivity (~ 1 W·m⁻¹·K⁻¹ for single flakes). - Hydrophilic surface terminations, moderate surface area (~ 20–50 m²·g⁻¹), stability up to ~ 600–730 °C depending on atmosphere. 	<ul style="list-style-type: none"> - Tunable surface chemistry, strong catalytic activity, good photothermal conversion, excellent electronic transport, and processability; - Ideal for catalysis, sensing, energy storage, and environmental applications. 	<ul style="list-style-type: none"> - Susceptible to oxidation, relatively lower mechanical strength than graphene, complex surface terminations. - Limited large-scale production maturity.
Borophene ¹⁰⁻¹³	<ul style="list-style-type: none"> - High electrical conductivity ($\sim 10^3$ S·cm⁻¹), good thermal conductivity (~ 100 W·m⁻¹·K⁻¹). - Theoretical surface area ~ 1900 m²·g⁻¹, high thermal stability (>700 °C). 	<ul style="list-style-type: none"> - Unique anisotropic electronic properties, lightweight structure. - Promising catalytic and nanoelectronic potential, tunable band structure. 	<ul style="list-style-type: none"> - Chemically unstable in air, difficult and costly synthesis. - Poor scalability, defect sensitivity, and limited commercial readiness.
Graphene ^{1,14-16}	<ul style="list-style-type: none"> - High electrical conductivity ($\sim 10^4$ S·cm⁻¹), very high thermal conductivity (≈ 4800–5300 W·m⁻¹·K⁻¹). - Large surface area (~ 2600 m²·g⁻¹), excellent thermal stability (>800 °C in inert atmosphere). 	<ul style="list-style-type: none"> - Outstanding charge transport, superior mechanical strength, high flexibility, chemical stability, and transparency. - Highly suitable for electronics, composites, and energy storage. 	<ul style="list-style-type: none"> - Low intrinsic chemical reactivity without functionalization, aggregation tendency in multilayers. - High production cost, defect control challenges, and scalability issues.

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