Scalable Graphene Via Top-Down Routes: From Production Technologies to Sustainability Assessment

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Abstract

Graphene has been widely celebrated as a “wonder material” due to its exceptional electrical, optical, mechanical, and thermal properties. Graphene has grown from laboratory curiosity to a material of growing industrial interest [1], with applications spanning from energy storage to electronic devices. Despite the exceptional intrinsic properties of Graphene, the industrial scale up is proving to be moderate from laboratory trials. In lab-scale environments, graphene is produced in gram quantities under controlled conditions, where material quality, layer number, and defect density can be optimised without strong constraints on cost, throughput, or reproducibility. However, in industrial conditions, the scenario is a bit different where the main focus is on tonne-scale production, consistent material characteristics, process robustness, and economic viability. This disconnection between these two regimes has been a bottleneck for graphene’s commercialization [2]. Here, we conducted a systematic assessment of various methods and industries and in the global graphene market that produce graphene through the **Top-down** approaches like Liquid phase exfoliation, Plasma expansion, Plasma functionalization, and electrochemical exfoliation, for various applications like polymer compounding with graphene loading, roll-to-roll printed electronics, thermal management paste/pads and so on. The production rate and capacity are studied by assessing their technology for scaling up the graphene production for companies like “**First Graphene**”, with continuous, high-throughput exfoliation **100 t yr^{-1}** plant capacity, “**Black Swan**” focusing on Graphene scalable exfoliation and master batching, currently **40 t yr^{-1}**, “**Haydale**” focusing on plasma functionalisation & ink production with **2 t yr^{-1}.** The study further examines the underlying science governing top-down graphene production, including interlayer bonding in graphite, exfoliation energetics, solvent–graphene interactions, electrochemical intercalation mechanisms, and defect generation during liquid-phase, plasma-assisted, and electro-chemical processes. Furthermore, **Techno-economic analysis** is performed along with sustainable production [3] to evaluate capital and operating costs, energy intensity, yield, and cost per kilogram for application-specific top-down production techniques based on industry requirement. **Life cycle Assessment** for the Top-down approach was studied using **OpenLCA** to assess environmental Impacts, including climate change, resource depletion, human toxicity, and ecosystem damage, and to produce a unified score. The integrated science-to-industry-to-assessment framework presented in this work aims to provide a realistic and application-oriented evaluation of **top-down** graphene technologies, supporting their scalable, economically feasible, and environmentally responsible industrial deployment.

References

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[3] Abimannan Sethurajaperumal, Eswaraiah Varrla, High-Quality and Efficient Liquid-Phase Exfoliation of Few-Layered Graphene by Natural Surfactant, ACS Sustainable Chemistry & Engineering, 10 (2022), 14746-14760.

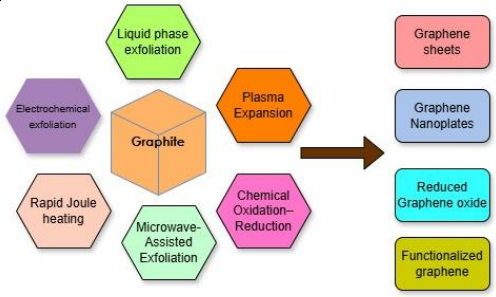

Figure 1: Overview of top-down graphene production routes from graphite to few-layer graphene suitable for industrial scale-up.