Ecofriendly Reduction of Graphene Oxide Using Extremophile Bacteria

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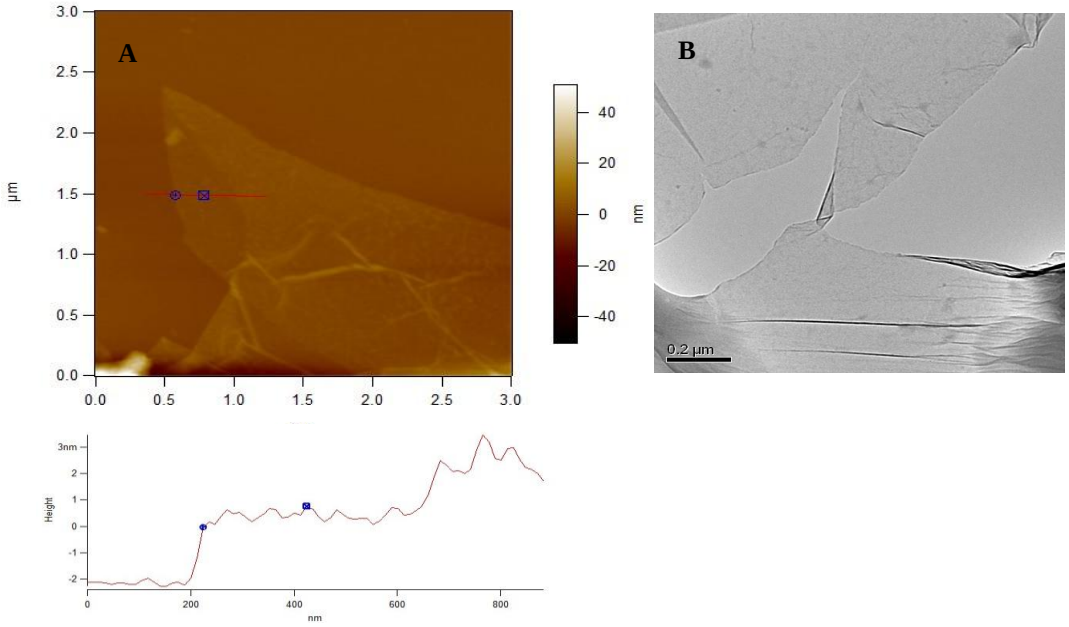
Graphene shows tremendous potential for applications including high frequency transistors, fuels cells, biosensors, and transparent conducting electrodes. These wide range of applications necessitate a simple, inexpensive, and environmentally friendly method for mass production of graphene. Recent reports indicate the emergence of chemically derived graphene using toxic chemicals [1,2]. In an effort to develop an environmentally friendly process, here we describe the synthesis of graphene by biological reduction of graphene oxide using extremophilic bacteria. It has been already reported that heterotrophic bacteria *Shewanella oneidensis* can utilize graphene oxide (GO) as its terminal electron acceptor in its respiratory pathway [3, 4]. As an alternative to metal reducing bacteria we used moderately halophilic extremophile *Halomonas* species [5] for biologically reducing GO. The GO was produced by modified Hummer's method using natural graphite powder. A wide range of concentrations of GO flakes were added to *Halomonas* growth medium for both aerobic and anaerobic bacterial reduction of the GO flakes. This approach enabled the extraction of large areas of single to multi-layer graphene sheets. The bacterially reduced GO was characterized using transmission electron microscopy (TEM), atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), and Raman spectroscopy. XPS measurements clearly showed increases in the intensity of C-C bond after biological reduction. We also compared the probability of GO reduction in the presence as well as in the absence of oxygen, with results showing more effective GO reduction under anaerobic conditions rather than aerobic. The ability of *Halomonas* to reduce GO was further investigated using two different strains of *H. eurihalina* and *H. maura*. Subsequent analysis showed that both strains were effective in the reduction of GO under the same culture conditions, where *H. eurihalina* was more efficient at reducing GO over a given incubation time. A wide range of concentrations of GO were added to the culture medium to test the reducing power of *Halomonas* over a constant time period, with the result that the rate of reduction increased as the concentration of the GO added was decreased. We believe that this extremophile bacteria based process is suitable for large scale production of graphene for industrial applications. Our approach is an ecofriendly, cost effective, and efficient method for producing large volumes of high quality graphene.

References

[1] R. Ishikawa, M. Bando, A. Sandhu, *Jpn. J. App. Phys*. **49** (2010) 06GC02.
[2] R. Ishikawa, M. Bando , Y. Morimoto , A. Sandhu, *Nanoscale Research Letters* **6** (2011)111.
[3] E. C. Salas, Z. Sun, A. Luttge, J. M. Tour, *ACS Nano,* **4** (2010), 4852.
[4] G. Wang, F. Qian, C. W. Saltikov, Y. Jiao, Y. Li, *Nano Res*. **4** (2011), 563.
[5] I. Llamas, A.D. Moral, F. Martinez-Checa, Y. Arco, S. Arias, E. Quesada, *Antonie van Leeuwenhoek* **89** (2006) 395.

Figures



A. AFM image showing *Halomonas* reduced graphene sheet with thickness curve
B. TEM image showing thin layer graphene sheet.