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Graphene Oxide as a Nanotechnological Tool for Enhancing Drought and Salinity Stress Tolerance in Crops

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Graphene, a novel form of nanomaterial, has found widespread usage in a variety of sectors due to its advantageous physical and chemical characteristics. Graphene oxide (GO) is a important graphene derivatives, which contains many oxygen-containing hydrophilic functional groups, such as carboxyl, carbonyl, epoxy and hydroxyl groups (Nazari *et al.*, 2020). GO has higher surface activity, better biocompatibility, and is easier to manufacture and functionalize than graphene. As a consequence, graphene oxide has garnered a lot of interest since its discovery in 2004 (Hu *et al.*, 2018). GO is presently employed in a variety of applications, including biological domains such as biosensor creation, photothermal therapy, and medicine delivery (Chong et al., 2014). Recent years have seen reports of the application of GO in agricultural output, notably in stimulating plant growth and development.

What is graphene oxide?

Graphene Oxide (GO) is a carbon-based nanomaterial obtained by the chemical oxidation of natural graphite or carbon nanofibers by strong oxidants. The exact chemical structure of GO cannot be specified due to the irregular density of the defects and the oxygen groups. Various models have been proposed since 1930 and several authors have classified GO to amorphous materials, but the model proposed by Lerf-Klinowski is widely acceptable (Trikkaliotis *et al.*, 2021) is given in Fig 1.. They describe GO as a 2-domain layer where graphene areas are randomly distributed to the oxidized plane. The oxidized plane is heavily decorated with hydroxyl and epoxy groups, while carboxyls and carbonyls terminate the edges and the defects/holes. The popularity of this model was raised by the confirmation of the 2-domain layer, with the assistance of nuclear magnetic resonance (NMR) spectroscopy and indeed the graphene areas are like isolated islands onto the oxidized plane which constitutes more than 70% of the flake. GO is considered as a non-stoichiometric metastable carbon compound with more than 2–3% defects that liberates CO_2 at temperatures as low as 45°C . Moreover, variations in oxidation degree might present to the flakes of the same batch and the size of the sp_2 domains increases with time

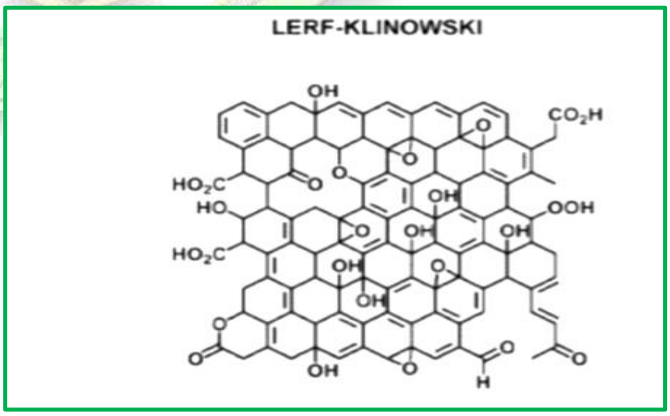
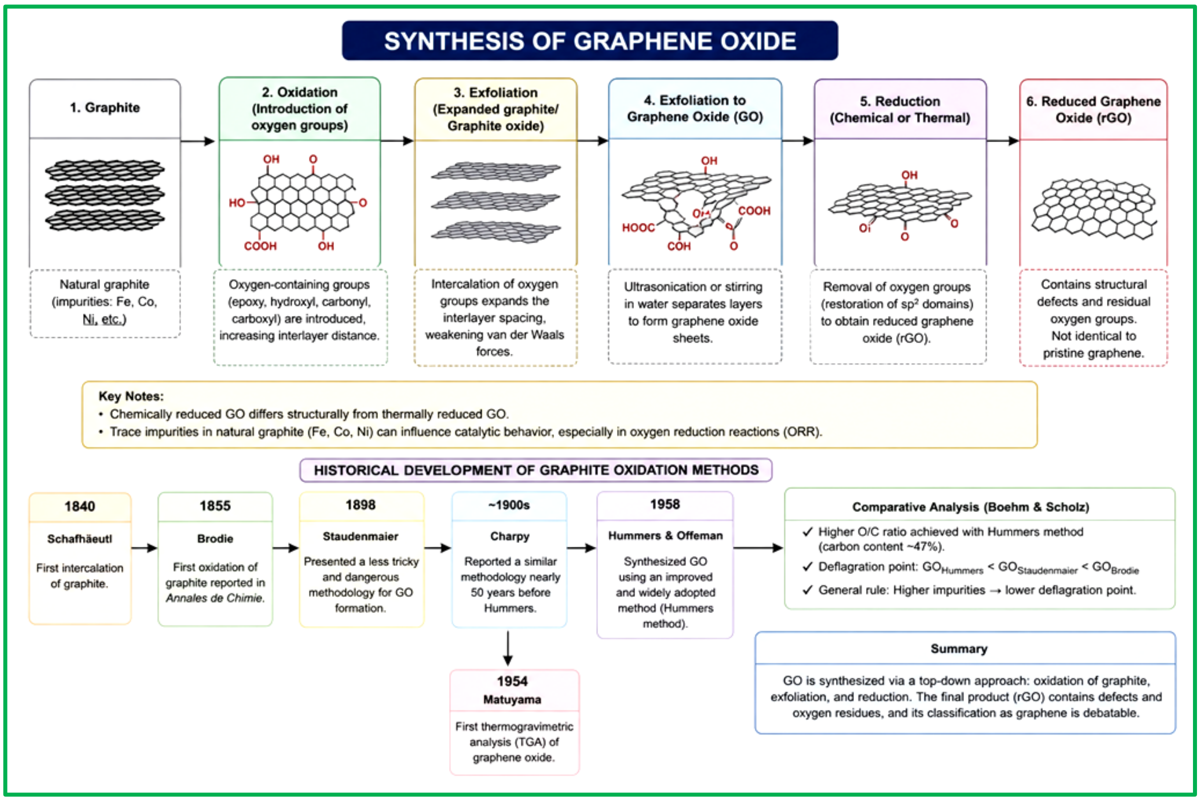


Fig 1. Structure of Graphene Oxide

Synthesis of graphene oxide



Application of Graphene Oxide for Enhancing Drought Tolerance in Plants

Drought is one of the most critical environmental stresses limiting crop productivity across agricultural systems. Recent studies demonstrate that graphene oxide (GO), a two-dimensional nanomaterial, can significantly enhance plant tolerance to water-deficit conditions across diverse species, including both field crops such as soybean and perennial fruit crops such as apple. GO application improves plant water status by enhancing water retention in aerial tissues and promoting the development of a more efficient root system. Treated plants exhibit increases in root length, surface area, diameter, and volume, which collectively facilitate improved water uptake under drought conditions. In addition, GO helps maintain physiological processes such as photosynthesis, particularly during prolonged stress. A key mechanism underlying GO-mediated drought tolerance is the enhancement of the plant antioxidant defense system. GO increases the activity of major antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), thereby improving the scavenging of reactive oxygen species (ROS). As a result, cellular damage indicators such as electrolyte leakage, malondialdehyde (MDA), and hydrogen peroxide (H_2O_2) are significantly reduced.

GO also regulates important biochemical and hormonal responses associated with drought adaptation. It elevates the levels of stress-related phytohormones, including abscisic acid (ABA), jasmonic acid (JA), and salicylic acid (SA), which play central roles in stress signaling and stomatal regulation. Furthermore, GO enhances the accumulation of protective metabolites such as proline, γ-aminobutyric acid (GABA), and various amino acids, contributing to osmotic adjustment and stress resilience. At the molecular level, GO induces the expression of key drought-responsive genes involved in antioxidant defense, osmoprotection, and stress signaling pathways. These include genes associated with osmolyte synthesis, transcription factors (e.g., DREB and ERF families), and enzymes regulating hormonal biosynthesis and oxidative stress mitigation. Thus, graphene oxide enhances drought tolerance through a multifaceted mechanism involving improved water uptake, strengthened root architecture, enhanced antioxidant capacity, regulation of phytohormones, accumulation of protective metabolites and activation of stress-responsive genes. These combined effects highlight the broad potential of GO as an innovative nanomaterial for improving crop resilience and sustaining agricultural productivity in drought-prone environments.

Role of Graphene Oxide in Enhancing Salinity Tolerance

Saline soil is generally defined as soil in which the electrical conductivity of the saturation extract (ECe) in the root zone exceeds 4 dS m^{-1} (approximately equivalent to 40 mM NaCl) at 25 °C, along with an exchangeable sodium percentage of around 15%. Such conditions lead to osmotic stress, ion toxicity, and nutrient imbalance, ultimately impairing plant growth and productivity. Recent studies demonstrate that GO can significantly enhance salinity tolerance, particularly in crops such as peanut. Seed priming with GO at an optimal concentration (e.g., 400 mg/ L) has been shown to improve germination performance, resulting in higher germination rates and faster seedling emergence. At the physiological level, GO modulates key metabolic processes, especially carbon and nitrogen metabolism, which are critical for early plant establishment.

Under saline conditions (e.g., 200 mM NaCl), GO-treated plants exhibit improved growth, enhanced photosynthetic efficiency, better plasma membrane stability, and increased nutrient uptake compared to untreated plants. GO also plays a crucial role in strengthening the antioxidant defense system by enhancing the activity of enzymes responsible for scavenging reactive oxygen species (ROS), thereby reducing oxidative damage associated with salt stress. At the molecular level, GO regulates gene expression and metabolite accumulation, influencing pathways related to photosynthesis, phytohormone signaling, antioxidant defense, and carbon and nitrogen metabolism. These coordinated responses contribute to improved stress adaptation and resilience.

Importantly, the beneficial effects of GO extend to yield improvement. GO-primed peanut plants have been reported to achieve a significant increase in productivity, with pod yield improvements of approximately 12.9% compared to untreated controls. In summary, graphene oxide enhances salinity tolerance through multiple mechanisms, including improved seed germination, regulation of metabolic pathways, enhancement of antioxidant defenses, stabilization of cellular structures, and activation of stress-responsive genes. These findings highlight the potential of GO as an innovative and effective tool for improving crop performance in salt-affected soils.

Reference

1. Trikkaliotis, D. G., Christoforidis, A. K., Mitropoulos, A. C., & Kyzas, G. Z. (2021). Graphene Oxide Synthesis, Properties and Characterization Techniques: A Comprehensive Review. *ChemEngineering*, *5*(3), 64. https://doi.org/10.3390/chemengineering5030064