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Graphene oxide carbon nanomaterial for sustainable agriculture: Synthesis, soil health, nutrient management and saline water remediation

Manikandan Ayiramkan[1], T Sherene Jenita Rajammal[1*], Parthasarathi Rengasamy[1], Baskar Murugaiyan[1], Senthil Kuppusamy[1], S Anandha Krishnaveni[2] & Arumugam Kanagavalli[1]

[1]Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli 620 027, Tamil Nadu, India

[2]Department of Agronomy, Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli 620 027, Tamil Nadu, India

***Correspondence:** T Sherene Jenita Rajammal, shereneraj@yahoo.co.in

Abstract

The increasing demand for sustainable agricultural production, coupled with declining soil health, inefficient nutrient use and poor irrigation water quality, necessitates the development of innovative and eco-friendly technologies. Among the nanomaterials, two-dimensional graphene oxide (GO) has gained attention due to their extraordinary physical and chemical properties, including high specific surface area, a better number of oxygen-containing functional groups, high adsorption capacity and surface chemistry. Green synthesis approaches using biomass, agricultural residues and plant extracts are highlighted for their potential to reduce environmental impacts and promote sustainable nanomaterial production. This review further discusses advanced characterisation methods such as Fourier transform infrared spectroscopy, x-ray diffraction pattern, Raman spectroscopy, scanning electron microscopy, transmission electron microscopy, Brunauer–Emmett–Teller surface area analysis and x-ray photoelectron spectroscopy for understanding their structure and function. These analytical techniques provide critical insights into the structural attributes that determine the agricultural performance of GO nanomaterials. Soil–nanomaterial interactions, adsorption of nutrients, controlled release of nutrients and removal of sodium ions from saline irrigation water were thoroughly assessed. Based on existing evidence, application of GO may enhance soil aggregation, water holding capacity, nutrient utilisation efficiency and irrigation water quality and help sustain crop production. However, challenges related to large-scale production, long-term environmental fate, biosafety, economic viability and regulatory standardisation have hindered widespread adoption in agriculture. Future research should prioritise scalable and cost-effective production technologies, long-term field validation, standardised risk assessment protocols and integration with precision agriculture to facilitate commercial adoption.

Keywords: carbon nanomaterial; graphene oxide; green synthesis; nutrient management; saline irrigation water

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1. Introduction

The challenge for agriculture is to produce more food while minimising the use of natural resources to promote environmental and economic sustainability. The world's agricultural systems are under pressure from several factors, such as rapid population growth, climate change, a reduction in soil fertility and water scarcity (1). Among all constraints, the degradation of soil quality alongside the extensive use of saline irrigation water have become major factors limiting crop productivity particularly in arid and semi-arid areas. Excessive soil salinity causes soil structure to deteriorate can cause the soils to become deficient in plant essential nutrients, disrupt water uptake, inhibit beneficial microbial activity and ultimately render plants unviable (1, 2). Intensive fertilisation and soil amendments using conventional methods may only yield short-term results and can lead to nutrient losses, contamination of ground water and environmental pollution. Thus, there is an urgent need for novel and environmentally friendly technologies that can simultaneously increase soil health, the use efficiency of nutrients and irrigation water quality. Due to their exceptional physicochemical properties and multi-functionalities, carbon-based nanomaterials (two-dimensional graphene oxide (2D GO)) are attracting significant attention for addressing agricultural challenges. Graphene oxide has garnered extensive interest due to its two- dimensional layered structure, high surface area, presence of oxygen-containing functional groups, excellent adsorption capacity compared to reduced GO, mechanical stability and abundant surface functional groups (3).

The unique properties of GO carbon nanomaterials allow for effective interaction with nutrients, water molecules, soil minerals, microorganisms and

undesirable ions and pollutants present in poor quality irrigation water, which leads to better nutrient retention, controlled nutrient release, improvement of soil physico-chemical properties, removal of undesirable ions and pollutants from poor quality irrigation water. The preparation of GO from biomass, agricultural wastes, biochar, coal derived carbon materials and reducing agents derived from plants has attracted increasing research interest (3, 4).

These green approaches are more suitable for agricultural applications compared to conventional chemical synthesis via Hummers' method, as they employ a modified Hummers' protocols with reduction in the use of hazardous chemicals, less environmental impact and the use of renewable feedstocks (5). The development of functionalised GO composites has been supported by advances in material engineering, which has allowed for the creation of composites that are more stable, with better adsorption capabilities and greater compatibility with soil ecosystems and has expanded their use from environmental remediation to precision agriculture and climate-resilient farming (1, 5). Beyond adsorption, application of carbon nanomaterials has been found to provide proper soil aggregation, increase water-holding capacity, increase the cation exchange capacity and stimulate beneficial microbes and reduce nutrient losses (leaching) in the soil. They can be used as a carrier of macro- and micronutrients and for controlled-release of fertilisers with enhanced nutrient-use efficiency (5).

In addition, a promising use of GO-based materials has been found in saline irrigation water remediation or reclamation using adsorption of sodium ions, dissolved salts, heavy metals and organic contaminants prior to its use in agriculture (Fig. 1). Although some progress has been made, there are still significant gaps in knowledge that include: laboratory-scale synthesis; short-term field-scale water reclamation; long-term environmental behaviour, soil microbiomic interactions, crop-specific response and economic feasibility (5, 6). Furthermore, the reviews were mainly dedicated to either the synthesis of GO, the development of nano fertilisers, or the purification of water, but relatively few combined these subjects in a holistic agricultural context. Thus, it is necessary to conduct a critical synthesis of recent developments to identify current gaps in knowledge, assess new technologies and determine future research directions (7, 8).

Accordingly, this review provides a comprehensive synthesis of recent advances in graphene oxide, emphasising green synthesis, physicochemical characterisation, mechanisms of soil–plant interactions, nutrient management and saline irrigation water remediation. It further identifies existing knowledge gaps and outlines future research priorities for the safe and sustainable agricultural application of these nanomaterials (8). Although several review articles have discussed graphene oxide synthesis, nano fertilisers, or water remediation individually, very few have comprehensively integrated these topics within the broader framework of sustainable agriculture. In contrast, the present review provides a holistic synthesis of recent advances in green synthesis, physicochemical characterisation, soil health improvement, smart nutrient management and saline irrigation water remediation using GO (1, 2).

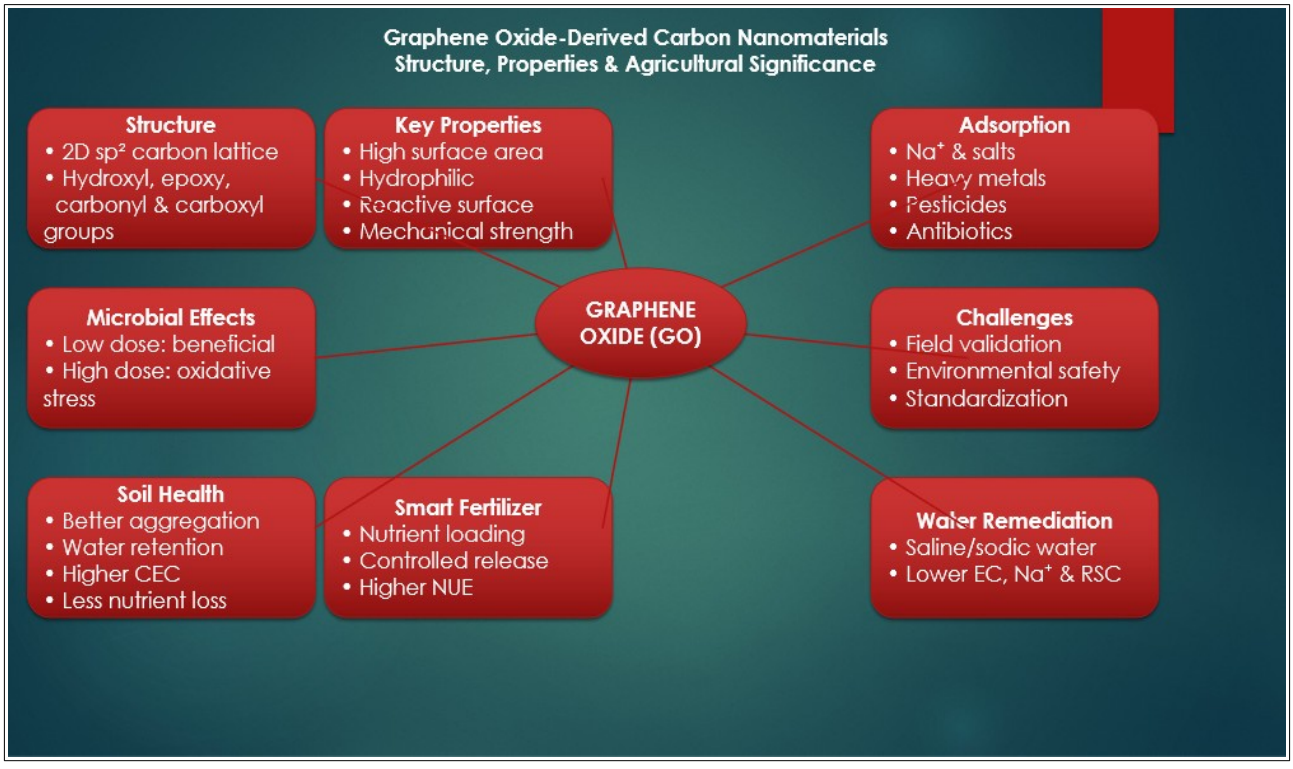


Fig. 1. Overview of the structure, key physicochemical properties and agricultural applications of graphene oxide (GO) carbon nanomaterials. Source: Original illustration prepared by the authors.

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Synthesis of graphene oxide carbon nanomaterials

The growing demand for environmentally friendly nanomaterials has accelerated research into green synthesis approaches for GO carbon nanomaterials. The conventional preparation methods of GO such as Hummers, modified Hummers, Brodie and Staudenmaier methods usually require the use of concentrated acids, strong oxidising agents and dangerous reducing chemicals (5, 8). While many methods achieve high oxidation efficiency in GO and maintain a reasonable structural quality, most of them produce toxic by-products and consume substantial quantities of chemicals and energy. These limitations have forced researchers to find new methods to make materials that are greener, safer and more environmentally friendly, while maintaining the same performance (9).

The principles of green chemistry were applied and the toxic reagents in the conventional synthesis were replaced in green synthesis by using the renewable biological resources and the energy and reaction conditions which are environmentally friendly. As a result, biomass-based carbon precursors, agricultural residues, forestry wastes, biochar, coal-derived carbon products and plant extracts are gaining popularity as carbon sources that are inexpensive, abundant, renewable and rich in carbon containing compounds. Along with reducing production costs, these renewable resources can help in valorising waste by producing and purifying functional nanomaterials from agricultural and industrial wastes for use in agriculture and the environment (9, 10).

Plant-mediated synthesis was given special attention because the extracts from plants are rich in a variety of phytochemicals, such as polyphenols, flavonoids, alkaloids, terpenoids, proteins, carbohydrates and organic acids, that are known to act as reducing, stabilising and capping agents (10). These molecules act as electron donors during the reduction process, thus restoring the graphitic carbon network in the process and reducing the use of harmful chemicals. Simultaneously, numerous phytochemicals adsorb onto the surface of graphene, which enhances the colloidal stability, surface functionality and biocompatibility. The plant-assisted synthesis is much safer than chemical synthesis (e.g. hydrazine or sodium borohydride) and yields fewer toxic residues and is more in line with sustainable agriculture (11).

Many medicinal and agricultural plants have been effectively utilised in the synthesis of GO derivatives via a green approach**.** The morphology of the particles, degree of reduction and surface functionalisation vary depending on the plant part used (e.g., leaves, roots, seeds, flowers and fruits) and the concentration of reducing metabolites. The plant species, extraction method, extract pH, reaction temperature, extract concentration and reaction time all affect the structural characteristics of the synthesised nanomaterials as shown in Table 1. Therefore, it is crucial to optimise the synthesis conditions in order to achieve GO derivatives with stable and uniform physicochemical properties and agricultural performance.

In addition to plant extracts, biomass-derived carbon materials are becoming increasingly crucial as sustainable graphene precursors. Agricultural residues (rice husk, wheat straw, sugarcane bagasse, coconut shell, corn stover, peanut shell, bamboo, sawdust and other lignocellulosic wastes) have a high carbon content and can be chemically activated, carbonised, or pyrolysed to yield graphene-like carbon materials (15). Such methods will not only decrease the disposal of agricultural wastes but will also produce value-added carbon nanostructures that have desirable adsorption properties. The resulting materials often have hierarchical pore structure, higher surface area with increased oxygen functional groups, that are useful for nutrient retention, contaminant adsorption and soil improvement (15, 16).

Table 1. Green synthesis strategies for graphene oxide carbon nanomaterials and their agricultural significance

Synthesis approach	Carbon precursor	Reducing/Stabilising agent	Major advantages	Agricultural applications	References
Modified Hummers method	Graphite	$KMnO_4/H_2SO_4$	High oxidation efficiency; reproducible GO production	Preparation of GO for functionalisation	(12)
Plant-mediated reduction	Graphene oxide	Plant extracts (polyphenols, flavonoids, alkaloids)	Eco-friendly, low toxicity, improved biocompatibility	Soil amendments, nanofertilisers	(12)
Biomass-derived synthesis	Rice husk, wheat straw, bagasse, bamboo, sawdust	Carbonisation/pyrolysis	Waste valorisation, renewable carbon source	Soil improvement, adsorption	(12,13)
Biochar-assisted synthesis	Agricultural biochar	Thermal activation	High porosity and adsorption capacity	Nutrient retention, water remediation	(13)
Coal-derived carbon synthesis	Coal char	Chemical activation	Low-cost precursor, high carbon yield	Saline water treatment	(13,14)
Functionalized GO composites	GO + metal oxides/biopolymers/clays	Surface modification	Enhanced stability and multifunctionality	Controlled nutrient release, contaminant removal	(13, 14)

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More recently, research has been directed towards the combination of green synthesis and functional modification. The GO sheets are now being used in combination with biochar, clay minerals, metal oxides, biopolymers and nutrient carriers to create multifunctional nanocomposites that have improved stability and agricultural benefits. Functionalisation can facilitate dispersion in aqueous media, avoid aggregation of the sheets, increase the number of adsorption sites and increase the mechanical strength. More importantly, these composite materials can have higher controlled nutrient release ability, better soil moisture retention and dissolved salt and contaminant removal ability from irrigation water. The multifunctionality of graphene oxide-based composites is the reason that they could be promising materials for climate resilient technologies in agriculture (15).

While these are positive steps, there are a number of challenges in the way of green synthesis being translated to large-scale agricultural applications. Nanomaterials can also be batch-to-batch variable, as the phytochemical composition of the plant extracts used to create the nanomaterials can change depending on the species, geographical location, season and extraction processes (15, 16). Likewise, biomass feedstocks vary in cellulose/hemicelluloses/lignin/ash ratios, which will affect carbon yield, graphitisation efficiency and surface chemistry. Standardised protocols for biomass selection, extraction, optimisation of the reaction and characterisation of the products are therefore necessary to enhance reproducibility and the industrial scalability. Furthermore, the life-cycle assessment and the techno-economic analysis and environmental safety assessment are still comparatively limited for many green synthesis technologies, which are important research priorities for further studies (17).

Green synthesis is a promising approach in the synthesis of GO that utilises renewable resources, environmentally friendly chemistry and principles of circular bioeconomy (Fig. 2). The selection of precursors, reaction optimisation and functional modifications are still being improved and will facilitate the development of cost-effective, scalable and environmentally friendly graphene-based materials for sustainable agriculture (18). These advances are the basis for the next steps towards characterisation and agricultural use of GO carbon nanomaterials for soil health enhancement, nutrient management and saline water irrigation remediation (19).

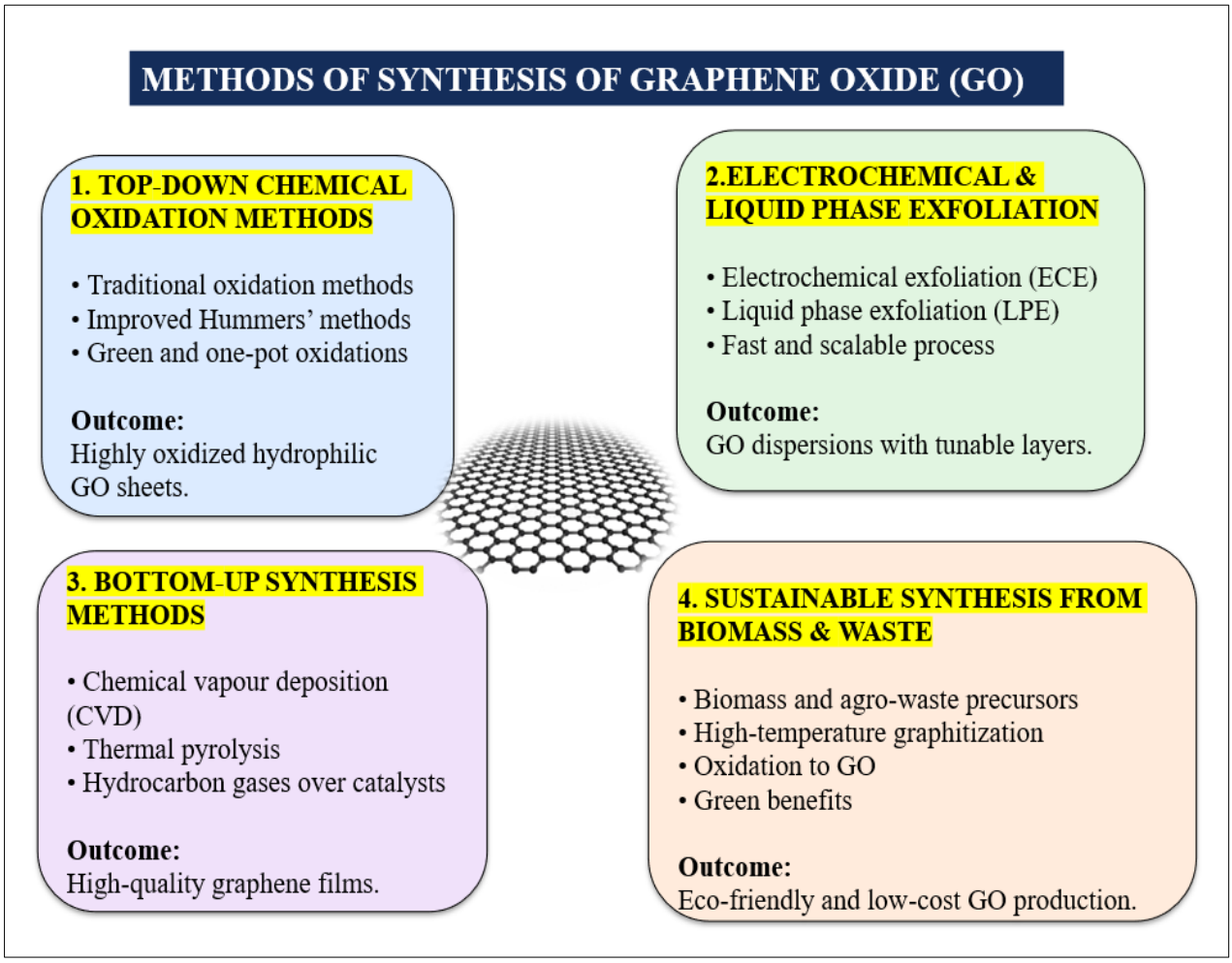


Fig. 2. Methods for the synthesis of graphene oxide (GO), including top-down oxidation, electrochemical and liquid phase exfoliation, bottom-up synthesis and sustainable biomass-based approaches. Source: Original illustration prepared by the authors.

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Functional characterisation of graphene oxide carbon nanomaterials

A detailed physicochemical characterisation is essential to understanding the structure, composition, surface chemistry and functional properties of GO. The physicochemical properties of GO have direct effects on its adsorption behaviour, nutrient loading capacity, mechanical stability and interactions with soil, water and plant systems, rendering accurate characterisation critical for predicting its agricultural performance (19). Because no single analytical technique can provide a complete picture of structure; hence a suite of techniques is normally used to gain a broad understanding of the material. Some of the most commonly used characterisation techniques include Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), Raman spectroscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), Brunauer-Emmett-Teller (BET) surface area analysis, X-ray photoelectron spectroscopy (XPS), energy-dispersive X-ray spectroscopy (EDS) and thermogravimetric analysis (TGA) along with zeta potential measurements (Fig. 3). Collectively, these complementary techniques provide comprehensive information on crystallinity, morphology, elemental composition, porosity, surface chemistry, particle size and thermal stability, enabling accurate prediction of agricultural performance (19).

Structural and surface functional group characterisation

The identification of oxygen-containing functional groups on the surface of graphene oxide by FTIR spectroscopy is one of the major methods employed. During the oxidation of graphite, hydroxyl groups (-OH), epoxy groups (C-O-C), carbonyl groups (C=O) and carboxyl groups (-COOH) are introduced, which are responsible for the great chemical reaction activity and adsorption properties of GO. In the typical FTIR spectrum, there is a broad absorption band in the range 3200–3500 cm^{-1}, which is due to the O-H stretching vibrations, while peaks are generally observed in the range 1710–1740 cm^{-1} and are assigned to carbonyl groups. The absorption bands observed between 1580 and 1625 cm^{-1} are typically assigned to graphitic (aromatic) C=C stretching. There are also several small peaks at 1220–1260 cm^{-1} and 1030–1100 cm^{-1} which are characteristic of epoxy groups and alkoxy groups, respectively as shown in Table 2. The changes in the peak intensities indicate the degree of oxidation and reduction efficiency and surface functionalisation after the chemical or green synthesis. The FTIR also provides confirmation of successful incorporation of polymers, metal oxides, or nutrient molecules during the composite preparation and it is an indispensable tool to assess graphene oxide used in agricultural applications.

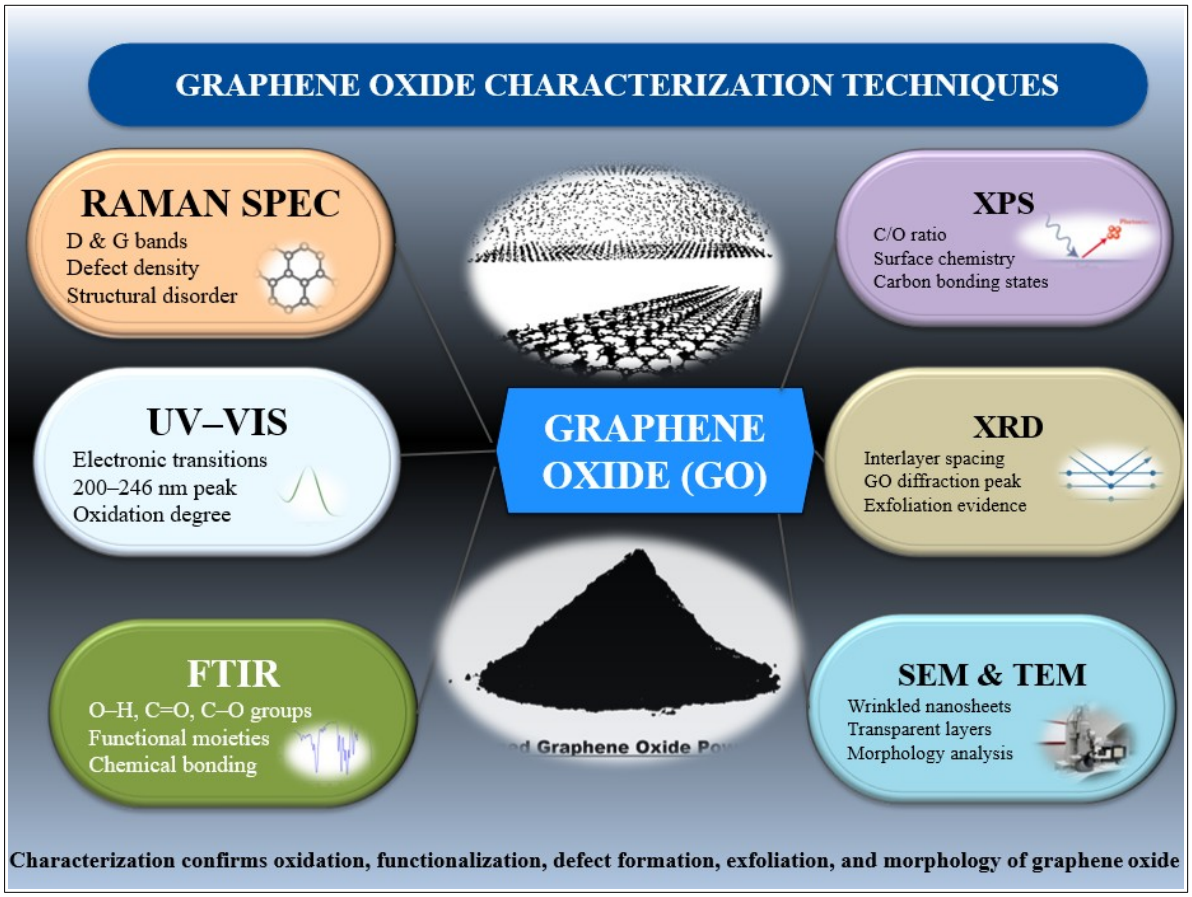


Fig. 3. Integrated functional characterisation of graphene oxide carbon nanomaterials and its significance for agricultural applications.

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Table 2. Structural features, surface functionalisation and dynamic chemical behaviour of graphene oxide (GO)

Structural feature	Functional groups present	Location on GO sheet	Chemical/Physical role	Key references
Basal plane oxidation	Hydroxyl (–OH) and Epoxide (C–O–C) groups	Flat surface regions of graphene oxide nanosheets	Disrupts sp^2 carbon network, increases hydrophilicity, enhances dispersion in water and provides active adsorption sites	(20)
Edge functionalisation	Carboxyl (–COOH) and Carbonyl (C=O) groups	Sheet edges and defect boundaries	Imparts acidic behaviour, improves ion exchange capacity and facilitates chemical modification and cross-linking reactions	(20, 21)
Hybridisation transformation	Conversion of sp^2 to sp^3 carbon hybridization	Oxidized carbon domains	Alters electronic conductivity and induces structural distortion in the graphene lattice	(21)
Defect-associated chemistry	Oxygenated defect sites and vacancies	In-plane structural defects	Generates highly reactive regions for adsorption, catalysis and interaction with metal ions	(21)
Dynamic structural evolution	Formation of additional oxygen functionalities in aqueous medium	Entire GO framework under hydration	Causes continuous structural rearrangement and progressive oxidation in water systems	(20, 21)
Surface acidity development	Dissociation of acidic surface groups releasing H_3O^+ ions	Hydrated GO interfaces	Contributes to proton conductivity, colloidal stability and pH-responsive behavior	(21, 22)
Water–GO interaction mechanism	Water-assisted oxidation and hydrolysis reactions	Aqueous GO suspensions	Enhances functional group density and modifies physicochemical stability over time	(22)

Crystallographic characterisation

The information obtained by XRD is valuable for understanding the crystal structure, interlayer spacing and transformation of the structures during oxidation and reduction processes. The diffraction peak for natural graphite is typically very strong in the vicinity of 26.5° for the (002) plane and has an interlayer spacing of about 0.34 nm (23). After oxidation this peak is either completely removed or significantly reduced and a new diffraction peak is usually observed at 9–12°, which corresponds to an increase of the interlayer distance due to the existence of oxygen-containing functional groups and water molecules between graphene layers (23, 24). The diffraction peak tends to move towards higher diffraction angles upon successful reduction/thermal treatment, indicating partial restoration of the graphitic structure. The XRD is therefore a very useful method to confirm the oxidation of graphite, assess the crystallinity of the compound and monitor changes in structure after functionalisation or formation of composites (24).

Defect and graphitic structure analysis using Raman spectroscopy

Raman spectroscopy is considered as one of the most informative methods for characterisation of structural defects and graphitic ordering in graphene-based materials (25). The D band (around 1340–1360 cm^{-1}) is due to the lattice disorder and the presence of defects, while the G band (around 1580–1600 cm^{-1}) is attributed to the in-plane vibration of the sp^2 carbon atoms. The intensity ratio of the D and G bands ID/IG is commonly employed to assess the order/defect density of the structure (23, 24). An increase in this ratio is usually associated with successful oxidation/reduction or functionalisation, whereas a decrease indicates the restoration of the graphitic network. Surface defects and oxygen functionality are crucial factors that affect the performance of agriculture and Raman spectroscopy plays an important role in understanding the structure–property relationships in GO carbon nanomaterials (26).

Morphological characterisation using scanning electron microscopy

Scanning electron microscopy (SEM) has been widely used to investigate the surface morphology of GO and its microstructural properties. Oxidation and exfoliation of graphite layers give rise to thin, wrinkled, folded and sheet-like structures, as exemplified by typical SEM images (27, 28). Surface wrinkles and corrugations enhance the surface area and offer many adsorption sites for nutrient ions and dissolved pollutants. The SEM also provides the ability to view aggregation, pore formation and the successful deposition of the nanoparticles, polymers or mineral phases on the graphene sheets. Qualitative and semi-quantitative elemental composition, which can be confirmed by EDS, is another advantage of SEM when used in conjunction with EDS. These morphological features are vital for assessing functionalised GO composites for nutrient delivery and water purification (20, 29).

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Transmission electron microscopy

Transmission electron microscopy (TEM) can directly image GO sheets at nanometre resolution. In a typical TEM image, it is possible to see the ultrathin graphene oxide sheets, which are transparent and exhibit characteristic wrinkles, folds and overlapping layers, characteristic of the two-dimensional nature of GO (21, 23, 30). High resolution TEM also gives structural information on lattice fringes and crystallinity and defects created in oxidation. In addition to TEM, selected area electron diffraction (SAED) patterns may be used to assess crystal ordering and successful exfoliation. The TEM provides a significantly higher spatial resolution than SEM, enabling the detailed investigation of nanoscale features of structure that affect the efficiency of adsorption as well as the mechanical strength and interaction with nutrients and dissolved salts (20, 31, 32).

Brunauer-Emmett-Teller surface area analysis

Brunauer-Emmett-Teller (BET) analysis is used to determine the specific surface area, pore volume and pore size distribution of graphene oxide materials. These parameters significantly impact the nutrient loading, removal efficiency of contaminants and adsorption capacity. Materials with higher surface areas tend to have higher adsorption of sodium ions, heavy metals, nutrients and organic contaminants as they offer more active sites (33). Nitrogen adsorption–desorption isotherms can also be used to categorise pores as microporous, mesoporous, or macroporous materials. The high adsorption capacity of mesoporous GO composites and their high velocity diffusion of nutrient ions and water molecules have gained considerable attention and researchers are aiming at using them as a soil amendment and for irrigation water treatment (23).

X-ray photoelectron spectroscopy

The XPS technique is a very sensitive surface analytical method for elemental composition and chemical bonding states of graphene oxide. Carbon and oxygen are generally characteristic features of survey spectra, while high resolution Carbon spectra can distinguish the C–C/C=C, C–O, C=O and O–C=O functional groups (33). The C/O atomic ratio derived from the XPS is often used as a measure of the degree of oxidation and the efficiency of reduction. The change in binding energies after functionalisation also offers evidence of successful incorporation of metal oxides, polymers or nutrient species. The sensitivity to the surface makes XPS to be one of the most reliable methods to assess surface chemical changes, which reflect adsorption behaviour and environmental performance of graphene oxide (1).

Integration of characterisation techniques for agricultural applications

Comprehensive characterisation is used to define the structure and agriculture performance correlation for graphene oxide. The regulation of nutrient adsorption and ion exchange is governed by surface functional groups, which can be identified by FTIR and XPS, while the mechanical stability and the accessibility of the adsorption sites are regulated by the crystallinity and by the interlayer spacing, which can be determined by XRD (9, 10). Morphological characters gained from the SEM and TEM analysis indicate both the sheet architecture and the development of pores, while the BET analysis provides a numerical estimate of surface area that can be used for nutrient retention and contaminant removal. Complementary use of both approaches allows scientists to design materials to enhance soil health and slow the release of nutrients and remediate saline irrigation water. Ongoing progress in the standardisation of the characterisation protocols will help to compare the findings from different studies and speed up the introduction of graphene oxide applications in the field of agriculture from the lab to the field (22, 23). Future efforts should focus on standardised characterisation protocols to improve reproducibility, facilitate comparison among studies and accelerate the translation of GO from laboratory research to field-scale agricultural applications (17, 18, 20).

Mechanisms of graphene oxide carbon nanomaterials in soil-plant systems

Graphene oxide-based carbon nanomaterials (CNMs) hold great promise for sustainable agriculture mainly due to their unique physicochemical properties and the complex interactions they build within the soil–plant–water continuum (34). The GO materials can affect soil physical properties, nutrient dynamics, microbial activity, root physiology and water quality all at once, unlike conventional soil amendments which only affect one aspect. The multifunctional interactions are controlled by adsorption, ion exchange, electrostatic attraction, hydrogen bonding, π–π interactions, redox reactions and surface complexation. Understanding these mechanisms is essential for optimising agricultural performance while ensuring the safe and sustainable use of GO-based nanomaterials (34).

Adsorption and surface complexation

Adsorption is one of the primary mechanisms governing the environmental and agricultural performance of GO carbon nanomaterials. The high density of hydroxyl, epoxy, carbonyl and carboxyl groups along the graphene oxide surface offer many binding sites for dissolved ions and organic molecules. Electrostatic attraction, hydrogen bonding, ligand exchange and π–π interactions are the possible adsorption mechanisms that occur as a function of solution chemistry and surface charge as shown in Table 3. These mechanisms allow GO to trap nutrients, like ammonium and to bind potassium, phosphate, sodium ions, heavy metals and organic contaminants from the irrigation water (Fig. 4). The large specific surface area further boosts adsorption capacity by providing more active surface for nutrient retention and decreases the mobility of contaminants in a farming system.

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Table 3. Representative quantitative performance of graphene oxide carbon nanomaterials in agricultural applications

Application	Graphene oxide carbon nanomaterials quantitative finding	Experimental condition	References
Na^+ adsorption	200–1700 mg g^{-1} depending on adsorbent modification	Batch adsorption	(35)
Heavy metal adsorption	Pb^{2+}: 250–600 mg g^{-1}; Cd^{2+}: 100–300 mg g^{-1}; Cu^{2+}: 120–400 mg g^{-1}	GO composites	(35)
*EC reduction	Typically 25–60 %	Saline irrigation water treatment	(35)
*SAR reduction	Approximately 30–70 %	GO composite adsorbents	(36)
*RSC reduction	Approximately 40–80 %	Laboratory studies	(35, 36)
Nitrogen-use efficiency	15–40 % increase	GO-based slow-release fertilisers	(36)
Phosphorus-use efficiency	10–35 % increase	GO nanocarriers	(35, 36)
Root biomass	15–45 % increase at low GO doses	Pot experiments	(37)
Beneficial GO concentration	10–100 mg L^{-1} (hydroponics) or 10–100 mg kg^{-1} soil	Most crops	(36, 37)
Phytotoxicity threshold	Frequently >200–500 mg L^{-1} or >250 mg kg^{-1} soil	Species dependent	(37)

EC: electrical conductivity (dS m^{-1}); SAR: sodium adsorption ratio; RSC: residual sodium carbonate (meq L^{-1}); NUE: nutrient-use efficiency (%); WHC: water-holding capacity (%); GO: graphene oxide.

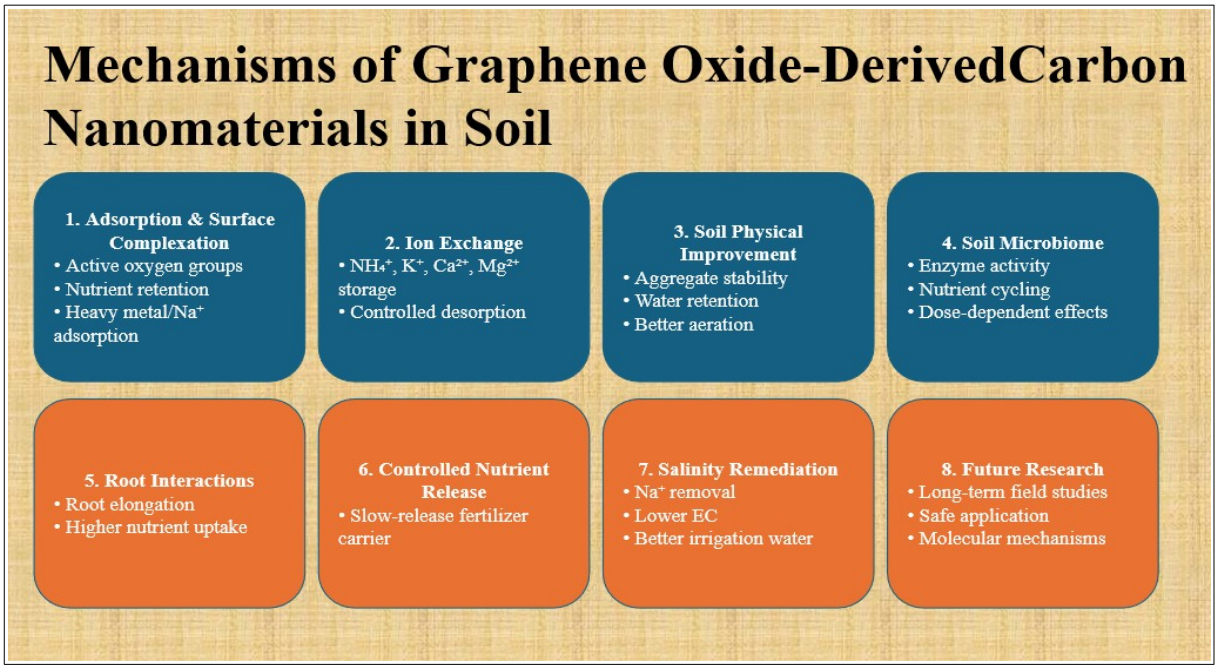


Fig. 4. Mechanisms of graphene oxide carbon nanomaterials in soil-plant systems for sustainable agriculture. Source: Original illustration prepared by the authors.

Ion exchange and nutrient retention

One of the most important functions of the GO is the reversible ion exchange that regulates the availability of nutrients. Oxygen-containing functional groups that are negatively charged can temporarily bind nutrient cations such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}), which are otherwise susceptible to leaching (22–24). Likewise, the positive charges generated by the surface modification can bind with the negatively charged nutrients like phosphate in the appropriate pH range (29). This reversible adsorption –desorption process acts as a nutrient reservoir which releases nutrients gradually as per the nutrient demand of crops, hence enhancing the nutrient use efficiency and reducing the nutrient losses. This is especially critical in sandy soils, or in intensively farmed agricultural systems where nutrients are likely to be leached (38). A laboratory adsorption study demonstrated that GO effectively retained nutrient cations through electrostatic interactions and surface complexation, thereby enhancing nutrient availability under controlled conditions (22). Another experimental study reported that GO-based materials reduced nutrient leaching losses by temporarily adsorbing essential cations and gradually releasing them in response to plant demand (39).

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Improvement of soil physical properties

The use of GO can drastically alter physical properties of soil which affects plant growth. They have two-dimensional sheet-like shaped morphology which helps them interact with soil particles and form aggregates, resulting in improved aggregate stability (2). The increased aggregation leads to better pore connectivity, aeration, water infiltration and decreases soil erosion. Further, the water adsorption capacity of GO is outstanding because of its hydrophilic oxygen-containing functional groups (3). This property also makes the soil more water holding, especially in coarse-textured soils and helps to provide more water to plants when there is a moisture deficit. Better soil structure also helps to assure deep rooting and better rhizosphere function (5, 40). The hydrophilic nature of GO, attributed to its abundant hydroxyl, carboxyl and epoxy functional groups, enables efficient adsorption and retention of water molecules. Greenhouse studies further showed that GO application increased the water-holding capacity of coarse-textured soils and improved moisture retention, thereby reducing drought stress and enhancing water availability for crop growth. In addition, pot experiments demonstrated that GO-amended soils exhibited improved root development and rhizosphere functioning because of enhanced soil structure and pore connectivity. These improvements facilitate deeper root penetration, enhance nutrient and water uptake and ultimately contribute to improved crop performance (7).

Interaction with soil microorganisms

Microorganisms in the soil have an essential function in the cycling of nutrients, breakdown of organic matter and plant health (6, 40). In recent years, the use of GO carbon nanomaterials has been shown to affect microbial communities in several ways. Graphene oxide can offer suitable microhabitats for microbial colonisation, promote the diffusion of oxygen and facilitate enzymatic nutrient transformations at optimal concentrations (6). Increases in microbial biomass and enzyme activities have been observed in several agricultural soils after application of GO which led to better mineralisation of nitrogen and availability of phosphorus. However, high concentrations can lead to oxidative stress, disrupt the membrane integrity of the microorganisms and change the microbial community (40). The biological response is therefore not only concentration dependent but also very much associated with particle size and surface chemistry of the nanomaterials, their exposure time and the properties of the soil and therefore a careful optimisation prior to field application is crucial (24).

Root-nanomaterial interactions

Roots are the main contact point between plants and GO. After soil application, the GO particles are attracted to the surface of the roots via electrostatic forces, hydrogen bonding and then affect the roots' physiology (14). Exposure to low concentration of GO has been reported to promote enhanced root elongation in several investigations, increased root lateral root formation and root surface areas (8). An enhanced root system promotes efficient nutrient and water uptake, thereby improving overall plant vigour. Conversely, excessively high concentrations may cause a reduction in the permeability of the plant's root membranes and also cause disruption to the plant's metabolism and growth. For this reason, positive results are typically linked to optimised application rates and not to indiscriminate application of nanomaterials (23).

Controlled nutrient release using graphene oxide

One of the most promising applications of GO in agriculture is the controlled delivery of nutrients. Loss of nutrients by volatilisation, run-off or leaching are common problems with conventional fertilisers which are low in nutrient use efficiency (34, 41). Functionalised GO can be used as an effective carrier because of its large surface area that can adsorb nutrient ions on its surface and gradually release it when the soil environment changes. Release rates are affected by soil pH, moisture, microbes and ionic composition which can help to synchronise nutrient availability and crop demand. This has the additional advantage of increasing the fertiliser-use efficiency and decreasing the pollution of the environment due to over-fertilisation (34).

Another critical aspect where GO carbon nanomaterials play a role in sustainable agriculture is its use for remediation of saline irrigation water. Excessive sodium levels in soils cause poor soil structure by removing calcium and magnesium from exchange sites, which results in dis-associating the soil aggregates and reduces infiltration and soil hydraulic conductivity (42, 43). Graphene oxide-based adsorbents not only adsorb heavy metals such as selected heavy metals and dissolved organic contaminants, but also bind sodium ions by electrostatic attraction, ion exchange and surface complexation. Reduction of sodium concentration and electrical conductivity makes irrigation water of better quality, reduces sodium hazard and prevents secondary soil salinisation. Therefore, GO adsorbents have huge potential for integrated soil/water management, especially for the salt affected agricultural areas (6).

Applications of graphene oxide carbon nanomaterials in soil health improvement

Soil health is a critical pillar for sustainable farming and determines soil nutrient cycles, water availability, soil microbes and long-term crop productivity. Soils, however, have been subjected to intensive cultivation, over fertilised, eroded, salinised and depleted of organic matter in many parts of the world, with negative consequences (1, 8). The impacts of these changes have affected soil quality by decreasing fertility, soil structure and exposure to stresses imposed by climate change on cropping systems**.** Therefore, a significant amount of research has been undertaken to create multifunctional soil amendments that would have multiple roles, improving soil physical, chemical and biological characteristics (12). In this regard, GO are showing growing interest due to their unique structural properties which allow several positive interactions in the soil. Recent studies show that when applied at proper

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concentrations (5 and 30 %), GO based materials have been shown to enhance soil aggregation and water holding capacity, while at the same time regulating the release of nutrients and encouraging beneficial microbial processes (Fig. 5). Across greenhouse and laboratory studies, GO applications of approximately 10–100 mg kg^{-1} soil generally improves root growth, microbial activity and water retention, whereas concentrations above approximately 250–500 mg kg^{-1} frequently induce oxidative stress, membrane damage and microbial inhibition, indicating a relatively narrow optimum application range (20, 29).

Improvement of soil structure and aggregate stability

The physical properties of soil strongly influence root development, porosity, infiltration and erodibility. Stable soil aggregates allow for the movement of water and gases to be more efficient and prevent organic matter from decomposing too quickly (34). The structure of graphene oxide is an ultrathin, 2-D sheet structure, which has oxygen-containing functional groups to readily interact with clay minerals, soil colloids and organic matter (28, 41). The interactions cause bridging of particles and formation of aggregate, leading to better structural stability. Improved aggregation means that the soil is less compacted, has more continuity of pores and provides a better environment for root growth. In degraded soils and soil under salt conditions, better aggregate stability can help improve infiltration and crop growth due to the dispersion of clay particles (31, 44).

Enhancement of soil water-holding capacity

Limited soil moisture is a major constraint to crop productivity particularly under drought and in coarse-textured soils (35). Due to the presence of many hydroxyl, epoxy and carboxyl functional groups, graphene oxide is hydrophilic and can adsorb and retain large amounts of water. The addition of GO to the soil helps to reduce transpiration losses and extend the moisture supply to the soil and increases water-use efficiency (37, 38). Experimental work has shown that the moisture holding capacity of soils treated with GO is higher than for untreated soils and plants can continue to have physiological activity for longer periods under water deficit. Better soil moisture also leads to higher microbial activity and nutrients spread in the rhizosphere and thus soil fertility (45).

Regulation of soil nutrient dynamics

Good nutrient cycling is crucial for good productive agricultural soils. The main mechanism of influence of graphene oxide on nutrient dynamics is the adsorption, ion exchange and gradual release of nutrients (26). They have a high specific surface area and functional groups that have a negative charge which will bind nutrient cations such as NH_4^+, K^+, Ca^{2+} and Mg^{2+} and prevent the loss of nutrients from leaching. Functionalised GO composites can also be used to adsorb phosphate under optimal soil conditions and make it available to plants over long periods of time (6, 7). The use of GO-based materials reduces nutrient runoff and groundwater pollution and increases fertiliser use efficiency, acting as temporary reservoirs for nutrients. The ability to conserve nutrients and to release them slowly plays an important part in sustainable nutrient management.

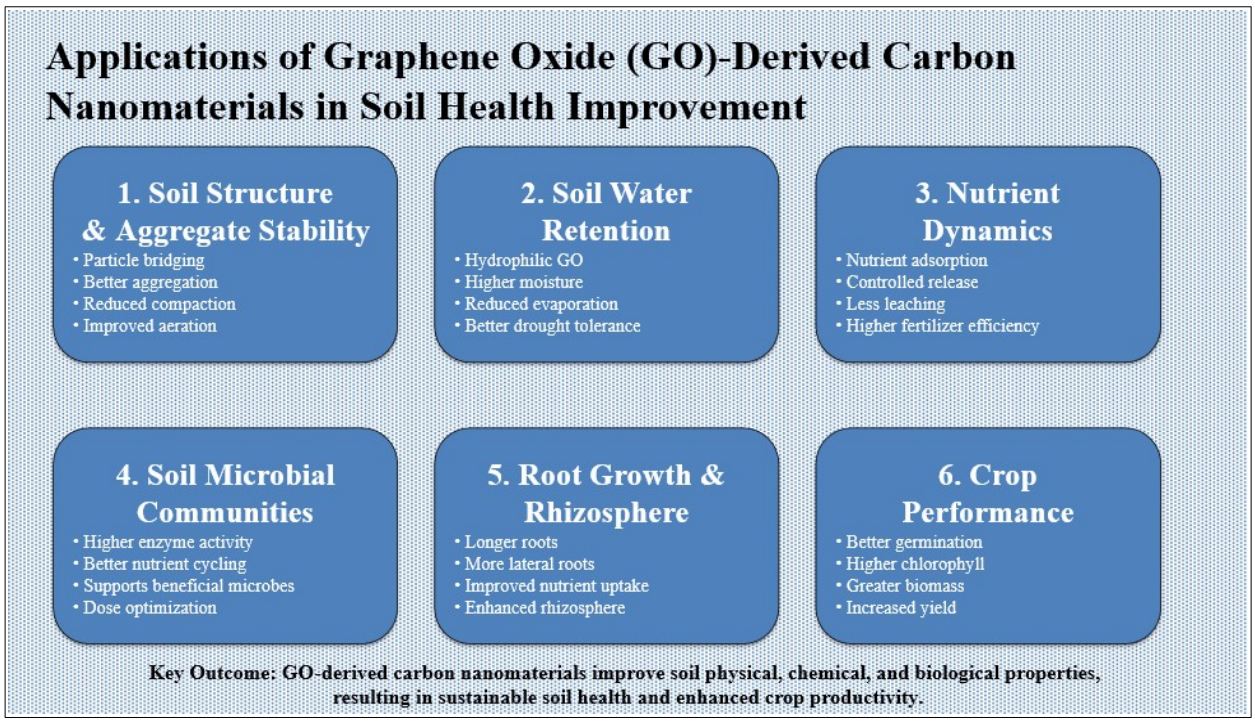


Fig. 5. Applications of graphene oxide carbon nanomaterials in soil health improvement and sustainable crop production. Source: Original illustration prepared by the authors.

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Graphene oxide-based nanocomposites have recently been investigated as advanced nano fertiliser carriers because of their ability to regulate nutrient release and improve nutrient-use efficiency (12, 13). Recent studies have demonstrated that GO-coated and GO-based composite fertilisers significantly reduced nitrogen and phosphorus losses through leaching while maintaining sustained nutrient availability under laboratory and greenhouse conditions. The high surface area and abundant oxygen-containing functional groups of GO facilitate nutrient adsorption through electrostatic interactions, hydrogen bonding and surface complexation, resulting in synchronised nutrient release according to crop demand. Furthermore, GO-biochar and GO-polymer composites have shown superior nutrient retention capacity compared with conventional fertilisers by improving cation exchange capacity, reducing nutrient runoff and enhancing fertiliser recovery efficiency (19, 42, 43). Recent greenhouse and pot experiments also reported improved root growth, nutrient uptake and crop biomass following the application of GO-based controlled-release fertilisers, indicating their potential for enhancing sustainable nutrient management (34).

Effects on soil microbial communities

A diverse microbial community plays a key role in the regulation of decomposition, nutrient mineralisation and turnover of organic matter to support healthy soils. Emergent data indicate that the activity of microbes can be altered by nanomaterials based on GO both directly and indirectly (41, 46, 47). At carefully optimised concentrations, GO has been shown to stimulate microbial respiration, increase enzyme activities and enhance decomposition of plant residues. Enhanced urease, dehydrogenase and phosphatase activity has been linked to enhanced nutrient cycling and availability of nitrogen and phosphorus. Moreover, recent research shows that beneficial microbial inoculants could be used in conjunction with GO to enhance microbial establishment and soil biochemical functions in saline soils. However, high levels can adversely impact sensitive populations of microorganisms and dose optimisation should be done prior to field-scale application (47).

Recent advances have also demonstrated that GO can function as a microbial support matrix, facilitating the establishment of beneficial plant growth-promoting microorganisms (PGPM), including *Bacillus*, *Pseudomonas* and arbuscular mycorrhizal fungi, by providing protective microhabitats and improving microbial attachment on root surfaces (31, 48). Functionalized GO composites combined with biochar, chitosan, or biodegradable polymers have shown greater compatibility with beneficial microorganisms than pristine GO, resulting in enhanced soil biochemical activity, improved nutrient mineralisation and increased resilience of the rhizosphere under abiotic stress (48).

Enhancement of root growth and rhizosphere function

The rhizosphere is one of the most dynamic parts of the soil environment and is the site of interactions between roots, microorganisms and soil particles which control nutrient uptake and plant health (1). Root elongation, lateral root formation and root surface area have been reported as consistently stimulated with appropriate concentrations of the graphene oxide. These enhancements enable more exploration of the soil profile for greater water and mineral nutrient uptake. Increased root growth also increases rhizodeposition and hence benefits soil biology and microbial communities (2). Reactions of plants are, however, species dependent and concentration dependent stressing that crop specific application rates must be identified (28). Recent transcriptomic and physiological investigations also indicate that GO may regulate the expression of genes associated with root development, antioxidant defence and nutrient transport, suggesting that its beneficial effects extend beyond physical soil improvement to include molecular regulation of plant responses. However, these responses are highly dependent on GO concentration, particle size, surface functionalisation, crop species and soil properties (23, 25, 49).

Improvement of crop growth and productivity

The beneficial effect of GO based carbon nanotechnology on soil properties are ultimately seen in better crop performance**.** Together, these favour plant growth due to better soil structure, more available water, better nutrient retention and more active microbes (48). Field and greenhouse studies have shown that the application of GO at appropriate concentrations has resulted in increased germination rate, chlorophyll content, photosynthetic efficiency, biomass and grain production (27). More recently, it has been shown in the field scale that the use of graphene-based materials can change the positive microbial interactions in the rhizosphere, leading to better soil fertility and productivity in field agriculture (27). The above results indicate that the agricultural advantages of GO are not only based on their immediate stimulation of plants but are also closely related to the enhancement of soil ecosystem function (26, 27). The functionalised GO composites integrated with biochar, polymer matrices and micronutrient carriers have been reported to improve fertiliser-use efficiency while simultaneously enhancing crop productivity and reducing nutrient losses to the environment (24). In addition, emerging field investigations indicate that GO amendments can improve rhizosphere functioning by promoting beneficial microbial interactions, increasing nutrient mineralisation and enhancing soil enzymatic activity, thereby contributing to sustained soil fertility and long-term agricultural productivity (25). These findings suggest that the agronomic benefits of GO-based carbon nanomaterials arise from their ability to regulate soil ecosystem processes, improve nutrient cycling and strengthen plant resilience against abiotic stresses rather than through direct stimulation of plant growth alone (48).

Applications of graphene oxide carbon nanomaterials in smart fertiliser systems

With the rising demand for sustainable production systems in agriculture, the challenge to enhance nutrient-use efficiency and reduce the losses and contamination

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of fertiliser in the environment has become more intensive (38). The recovery efficiency of conventional fertilisers is typically low since a significant amount of nutrient application is not recovered by plant growth due to leaching, runoff, volatilisation and fixation (25, 37). These losses drive up production costs and result in eutrophication, greenhouse gas emissions and long-term degradation of soil and water resources. Therefore, the emergence of smart nutrient delivery systems has become a great goal in current agriculture. Graphene oxide have shown great potential because of the surface chemistry, excellent adsorption property and large specific surface area. These properties contribute to the ability of GO-based materials to serve as nutrient carriers, controlled release matrices and soil conditioners, resulting in better nutrient availability and fertilizer-use efficiency(29, 30).

Graphene oxide as a nutrient carrier

Graphene oxide has many hydroxyl, epoxy and carboxyl functional groups that are capable of interacting with nutrient ions by electrostatic attraction, hydrogen bonding and surface complexation (33). These interactions can help the GOs bind both positive and negative and negative nutrients and minimise the amount of immediate release into the soil solution**.** The nutrients contained in the GO-based carrier are released slowly depending on the soil moisture, pH and root activity unlike the conventional fertilisers which dissolve quickly after application. This controlled release helps to better synchronise nutrient supply with the crop's demand, higher nutrient recovery and lower leaching losses. In this context, GO-based materials are gaining great attention as potential ingredients of future nano fertilisers in sustainable agriculture (24, 33, 38).

Controlled release of macronutrients

Nitrogen, phosphorus and potassium are essential macronutrients required in relatively large quantities for plant growth. The conventional nitrogen fertilisers, on the other hand, tend to be readily hydrolysed and leached as nitrate in many agricultural soils, while many soils tend to immobilise phosphorus by precipitation and adsorption (33). The GO-based nanocomposites have been found to be effective in controlling nutrient release, which can be achieved by temporarily capturing the fertiliser ions on the surface of the material and slowly releasing them under favourable environmental conditions**.** Slow nutrient release extends the nutrient supply throughout the vegetative phase of the crop and decreases the required application frequency (23, 48). Experimental work has also shown that when GO-based carriers were used in fertiliser formulations, the N-use efficiency was improved, the amount of available phosphorus was increased and the amount of retained potassium was enhanced especially when applied in intensive agriculture in which nutrient losses are quite high (22).

Delivery of secondary and micronutrients

Besides macronutrients, GO have demonstrated a significant potential to carry calcium, magnesium, sulphur and micronutrients such as zinc, iron, manganese and copper. Soils used for agriculture are often deficient in micronutrients and soils with sufficient macronutrient levels often lack adequate micronutrient levels to support crop productivity (46, 50). The functionalised GO acts as a stable platform to load micronutrient ions into the GO and prevent the quick precipitation or fixation in soil. Slow release of nutrients ensures micronutrient bioavailability in the rhizosphere and balanced plant nutrition. These multifunctional nutrient delivery systems could result in lower repeated fertiliser application requirements, higher efficiency of nutrients use and better crop quality (26, 27).

Improvement of nutrient-use efficiency

In the sustainable nutrient management, improving nutrient-use efficiency (NUE) has emerged as one of the main goals, as the sole increase of inputs in the form of fertilizers is no longer economically and environmentally acceptable. The GO nanomaterials can enhance NUE in several complimentary ways (47)**.** The immediate losses of nutrients after fertilizer application are decreased by the adsorption of the nutrient ions. Second, the controlled nutrient release ensures nutrients are available in a manner that matches the needs of the plant. Thirdly, better soil aggregation and water holding capacity allows for more nutrient diffusion to plant roots. GO-based controlled-release fertilisers have been reported to improve nitrogen-use efficiency by approximately 15–40 % while simultaneously reducing nutrient leaching losses. Improvements in phosphorus availability ranging from 10 –35 % have also been reported depending on fertiliser formulation and soil type (47, 48).

Integration with organic amendments and biofertilisers

Recently, the study of the integration of graphene oxide with organic fertilisers, composts, beneficial microorganisms and biochar has been investigated in order to create multifunctional nutrient delivery systems (10, 14). These are integrated products that have the benefits of mineral fertilisers for quick nutrient availability and the benefits of organic amendments for long term use. The GO is a structural support that can absorb nutrients, enhance microbial establishment and control the release of nutrients. Biochar–graphene composites are often found to be more efficient at holding nutrients than either biochar or graphene, as they offer complementary functionality and pore structure (21). Likewise, by integrating with plant growth promoting microorganisms, there is potential to improve biological nitrogen fixation and phosphorus solubilization and nutrient cycling in the rhizosphere (46).

Role in precision agriculture

The goals of precision agriculture are to increase the efficiency of using a resource to its maximum level based on site-specific management of nutrient, water and crop inputs (26, 27, 45). The physicochemical characteristics of graphene oxide render them useful in the development of precision nutrient management strategies**.** They are loaded with nutrients and have a controlled release to minimise fertiliser application. In addition, research into the use of graphene-based materials is continuing for their integration with nanosensors that can monitor soil moisture, nutrients and environmental conditions in real

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time. These technologies could help manage nutrients data driven, increasing fertiliser efficiency and reducing the environmental impact (47).

Graphene oxide carbon nanomaterials for saline irrigation water remediation

High-quality irrigation water has become one of the major challenges facing global agriculture. Due to the scarcity of freshwater, climate change, overexploitation of groundwater and intrusion of seawater, many of the agricultural areas must use saline water or sodic water for irrigation (44, 49). Such water resources, however, help meet the irrigation requirement to some extent, but if used for too long time, they also cause soil salinisation, sodification and nutrient imbalance, which ultimately leads to a significant decrease in crop productivity.

High levels of sodium ions (Na^+), chloride (Cl^-), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) tend to have a negative effect on soil structure by dispersing the clay in the soil, reducing its hydraulic conductivity and limiting water infiltration (35, 36). Too much sodium also interferes with the uptake of important plant nutrients, like calcium, magnesium and potassium, causing nutritional disorders and physiological stress. Consequently, sustainable technologies capable of improving irrigation water quality and mitigating salt accumulation have become increasingly important. In recent years, GO-based materials have been identified as suitable multifunctional adsorbents due to their high adsorption capacity and their surface chemistry, which can be tuned (49).

Mechanisms of sodium ion adsorption

The GO are one of the most promising materials due to the excellent physicochemical properties. They have two-dimensional architecture building blocks, a high specific surface area and a good number of functional groups containing enough oxygen atoms, which offer a multitude of active sites for the adsorption of dissolved ions and contaminants. The hydroxyl, epoxy, carbonyl and carboxyl groups are distributed on the surface of GO which is useful for the efficient removal of sodium ions and other dissolved species from saline water by electrostatic attraction, ion exchange, hydrogen bonding and surface complexation. In contrast to the conventional adsorbents, which are usually effective at removing a specific category of contaminants, GO have a multifunctional behaviour, simultaneously removing inorganic ions, heavy metals and selected organic pollutants with good adsorption efficiency in repeated treatment cycles (20, 26).

There are multiple complementary mechanisms of adsorption of sodium ions when saline irrigation water is removed. The electrostatic attraction is between positive sodium ions and the oxygen functional groups on the GO surface (43, 49). Sodium ions and oxygen donor atoms in carboxyl and hydroxyl groups coordinate and are further stabilised by the surface complexation as shown in Table 4. Furthermore, the ion-exchange reactions enable partial removal of sodium ions by the presence of calcium, magnesium and/or hydrogen ions linked to the functionalised GO composites that can be adjusted. Because of its large surface area, small size and layered structure, GO has a high adsorption capacity and can reach equilibrium quickly. All these mechanisms combine to result in a substantial decrease in sodium concentration, electrical conductivity (EC) and sodium hazard (NaH) of treated irrigation water.

Table 4. Mechanisms and applications of graphene oxide (GO) in water desalination

Concept	Key features and mechanisms	Major outcomes / significance	Reference
Graphene oxide as a desalination material	GO possesses atomic thickness, high mechanical strength and abundant oxygen-containing functional groups	Enables selective ion rejection and ultrafast water transport	(50)
Frictionless nanocapillary water transport	Pristine graphene domains provide nearly frictionless channels for rapid water movement	Water permeation becomes several orders faster than classical fluid transport predictions	(50)
Capillary forces in go membranes	Narrow 2D nanochannels generate strong capillary action within stacked GO sheets	Accelerates spontaneous water infiltration into membrane layers	(50)
Structural defects and wrinkles	Defects, inter-edge gaps and wrinkles create vertical transport pathways across membranes	Enhances permeability and facilitates cross-membrane water migration	(50, 51)
Size exclusion mechanism	GO interlayer spacing acts as a molecular sieve restricting hydrated ions	Enables efficient salt rejection through steric hindrance	(51)
Dehydration penalty effect	Hydrated ions must partially lose hydration shells to enter sub-nanometer GO channels	Produces high energy barriers for ion transport while permitting water passage	(51)
Donnan electrostatic exclusion	Negatively charged GO functional groups repel co-ions and restrict counter-ion movement	Enhances overall salt rejection efficiency	(52)
Ion adsorption and coordination	Oxygen clusters and aromatic carbon domains interact with metal ions via coordination and cation–π interactions	Assists in selective ion trapping and contaminant removal	(52)
Hydration-induced swelling	Water intercalation expands GO d-spacing from ~6–7 Å to ~13.5 Å	Weakens ion sieving capability and reduces membrane selectivity	(51, 52)
Chemical cross-linking	Multivalent cations crosslink adjacent GO sheets	Improves mechanical stability and	(52)

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stabilisation	through coordination bonding	swelling resistance	
GO-Based reverse osmosis (RO) membranes	GO incorporated into thin-film composite polymer matrices	Improves water flux and salt rejection compared to conventional membranes	(51, 52)
Holey graphene oxide nanofiltration	Nanopores etched into GO sheets reduce transport resistance	Achieves very high water permeance while maintaining salt rejection	(52)
GO in pervaporation desalination	Crosslinked GO membranes operate under vapor transport conditions	Produces > 99.9 % salt rejection for highly saline industrial wastewater	(52)

Salinity and sodicity of irrigation water

Additionally, GO derived adsorbents have the capacity to enhance various irrigation water quality parameters that make water suitable for agricultural usage. Published laboratory investigations generally report reductions of approximately 25–60 % in electrical conductivity (EC), 30 –70 % in sodium adsorption ratio (SAR) and 40–80 % in residual sodium carbonate (RSC) following treatment with GO-based adsorbents, although the magnitude depends on adsorbent composition, dosage and initial water quality. The laboratory investigations showed that when treated with GO-based materials, there was a decrease in electrical conductivity value, SAR values, RSC and total dissolved solids. Reduction in sodium and increase in calcium-to- sodium ratio lessen the possibility of clay dispersion after irrigation and aid in maintaining soil aggregate stability and infiltration capacity. The removal of bicarbonate and carbonate ions at the same time additionally mitigates the alkalinity hazards, minimising the chance of secondary soil sodification on long-term irrigation. All these improvements enhance the suitability of marginal-quality water for agricultural use and will aid in sustainable management of the salt-affected soils (53).

Functionalised graphene oxide composites for water remediation

Although pristine GO possesses excellent adsorption capacity, the development of functionalised GO-based composite materials has attracted increasing attention because of their superior adsorption performance, enhanced mechanical stability and improved regeneration efficiency (50). Various materials, including iron oxides, magnesium oxides, calcium-based compounds, activated carbon, biochar, natural polymers (e.g., chitosan) and zeolites, have been incorporated with GO to enhance its adsorption properties. These functionalised composites provide additional active adsorption sites, reduce the aggregation of GO sheets and facilitate efficient recovery and reuse after water treatment (51, 52).

Among these composites, biochar-GO materials combine the high porosity of biochar with the reactive surface chemistry of GO, thereby enhancing the removal of dissolved salts, sodium ions and heavy metals from poor-quality irrigation water (53). Similarly, magnetic GO composites enable rapid separation from treated water using an external magnetic field, reducing operational costs and improving the feasibility of large-scale water treatment applications. Furthermore, these multifunctional composites exhibit enhanced adsorption kinetics, greater structural stability and improved reusability compared with pristine GO, making them promising adsorbents for sustainable agricultural water remediation (52, 53).

Adsorption kinetics and isotherm behaviour

Adsorption kinetics and equilibrium studies can also provide useful insights into the mechanisms of the removal of ions by GO based adsorbents. Many investigations have reported sodium adsorption to exhibit pseudo-second order kinetic behaviour, which implies that significant contribution from chemisorption (electronic sharing and exchange) to adsorption (53). The Langmuir isotherm model, which is usually applied to equilibrium studies, suggests relatively homogeneous active sites in the form of monolayer adsorption (54). The Freundlich and Temkin models are other possible systems that could be used, however, they are models of heterogeneous adsorption surfaces or multiple interacting ions. Choosing an appropriate adsorption model is a function of the characteristics of the adsorbent, the ionic composition of the solution, the experimental pH and the level of certainty (52, 53). These kinetic and equilibrium studies are crucial for the design of reasonable water treatment systems and for determining the optimum dosage of the adsorbent in the field. The GO and GO-derived composites exhibit high adsorption capacities because of their abundant oxygen-containing functional groups and large specific surface area. Representative adsorption capacities reported in the literature include approximately 200 to 1700 mg g^{-1} for sodium depending on adsorbent modification, while heavy-metal adsorption capacities commonly range from 100 to 600 mg g^{-1} for Pb^{2+}, Cd^{2+} and Cu^{2+} (54, 55).

Regeneration and reusability

Considering the economic viability of graphene oxide-based adsorbents, it is important to evaluate their potential for regeneration and reuse without significant loss of adsorption capacity (55, 56). Sites of adsorption have been restored after multiple treatment cycles with various methods of regeneration, such as dilute acid washing, alkaline treatment and salt desorption, which have been demonstrated to show encouraging results. Functionalised GO composites typically have higher structural stability than GO in comparison to GO alone and a high percentage of the adsorption capacity remains after repeated regeneration (53, 54). However, adsorption efficiency decreases over time because the active sites are being permanently occupied, distortions in the structure and partial material loss during manipulation. The establishment of robust regeneration strategies is still a major goal for minimising treatments costs and ease of commercialisation (57).

The use of conventional adsorbents like activated carbon, natural zeolites, ion-exchange resins and biochar for water purification has been used for a long time**.** These materials offer adequate removal of specific contaminants

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but may have adsorption capacity and/or regeneration efficiency or selectivity limitations for sodium ions (58). In comparison, GO has several merits such as a higher specific surface area, a higher density of functional groups, easiness in surface modification and better adsorption rate. But there are still costs associated with production and standardised synthesis protocols to overcome. This should therefore be the subject of future research, with the aim of achieving a balance between treatment efficiency and cost-effectiveness by combining graphene oxide with cheap natural adsorbents (55, 59, 60).

Limitations

Despite the promising results reported in recent studies, several limitations remain. Most available evidence is derived from laboratory and greenhouse experiments, whereas long-term field validation under diverse agroecological conditions is still limited. In addition, the physicochemical properties of green-synthesised GO carbon nanomaterials may vary because of differences in biomass sources, synthesis protocols and processing conditions, leading to batch-to-batch variability and reduced reproducibility (60). Beneficial effects are often observed only within a relatively narrow concentration range, while excessive application may induce phytotoxicity, oxidative stress, or adverse effects on soil microbial communities. Furthermore, the long-term environmental fate, persistence, biodegradation, trophic transfer and biosafety of these nanomaterials remain insufficiently understood. Addressing these limitations through standardised synthesis protocols, comprehensive risk assessment and long-term field investigations is essential before large-scale agricultural adoption.

2. Conclusion

Graphene oxide (GO) carbon nanomaterials have been identified as attractive multi-functional materials for sustainable agriculture because of their high structure-specific surface area, large number of oxygen-containing functional groups, remarkable adsorption ability and tunable surface chemistry. This review focuses on the recent developments in the green synthesis, functional characterisation and application of GO in soil health enhancement, nutrient-use efficiency and saline irrigation water remediation. The evidence available suggests these nanomaterials have the potential to enhance soil aggregation, water holding capacity, cation exchange capacity and controlled nutrient release and to adsorb sodium ions, heavy metals and other contaminants in poor irrigation water. The reported benefits, however, are dependent on a variety of synthesis techniques, material properties, application rates, soil condition, crop species and environmental condition. Moreover, most studies available are confined to lab and greenhouse experiments, with very limited studies for validation in the field. However, further studies should be directed towards the development of scalable green synthesis methods, standard production processes and multifunctional GO composites for various agricultural systems. In-depth environmental fate, biosafety, life cycle, techno-economic and regulatory studies are crucial for responsible agricultural deployment. Overall, GO has considerable potential to transform sustainable agriculture by improving soil health, enhancing nutrient-use efficiency and enabling efficient irrigation water management. Realising this potential will require interdisciplinary research, standardised production methods, rigorous environmental safety assessments and large-scale field validation to facilitate responsible commercial adoption. Unlike previous reviews that primarily focused on individual aspects of graphene oxide applications, this review integrates recent advances in green synthesis, material characterisation, soil health enhancement, nutrient management and saline irrigation water remediation within a single comprehensive framework. This integrative approach provides a broader understanding of the multifunctional role of GO carbon nanomaterials and highlights future research priorities for their sustainable agricultural application.

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Authors' contributions

MA conceived the review topic, conducted the literature survey, synthesised the scientific information, prepared the figures and tables and wrote the original manuscript draft. TSJR conceptualised and supervised the review, provided scientific guidance and critically reviewed and edited the manuscript. PR, BM, SK, SAK and AK contributed to the critical review of the literature, interpretation of scientific findings and revision of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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