

# Unveiling the Potential of Graphene Oxide as a Multifunctional Platform for Active Food Packaging: Properties, Applications, and Prospects

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## Abstract

The demand for active food packaging is rapidly increasing as the food industry seeks more effective strategies to extend shelf life, preserve quality, and ensure safety beyond the limits of conventional materials. Traditional packaging often suffers from high gas permeability and limited antioxidant or antimicrobial activity, driving the exploration of nanotechnology-based solutions. Among emerging candidates, graphene oxide (GO) has attracted significant attention

due to its distinctive structure of atom-thin sheets decorated with oxygen-containing groups and its exceptionally large surface area. These characteristics enable GO to reinforce polymer matrices, improving mechanical strength, thermal stability, and barrier properties, while also providing multifunctional bioactivity. Experimental evidence shows that GO exhibits antimicrobial effects through microbial membrane disruption, reactive oxygen species (ROS) generation, and nutrient exchange interference, while its antioxidant capacity allows radical scavenging and lipid oxidation inhibition. Applications have been demonstrated across polymer nanocomposites, surface coatings, and smart sensors, where GO not only strengthens packaging materials but also functions as a freshness indicator for perishable foods such as meat, dairy, fruits, and fish. Despite these advantages, unresolved challenges include toxicity concerns, particle migration risks, and the absence of harmonized international regulations. Future research must therefore emphasize comprehensive toxicological assessment, green and scalable synthesis approaches, and integration with biodegradable polymers. Addressing these gaps could establish GO as a safe, sustainable, and innovative platform for next-generation active and intelligent food packaging.

**Keywords:** Graphene oxide, Active packaging, Nanocomposites, Barrier properties, Food security

### Abbreviations

GO: Graphene Oxide  
ROS: Reactive Oxygen Species  
PLA: Polylactic Acid  
PVA: Polyvinyl Alcohol  
PBAT: Poly(butylene adipate-co-terephthalate)  
OTR: Oxygen Transmission Rate  
WVTR: Water Vapor Transmission Rate  
SML: Specific Migration Limit  
EFSA: European Food Safety Authority  
FDA: Food and Drug Administration  
FAO: Food and Agriculture Organization  
WHO: World Health Organization

### Introduction

The modern food sector faces significant obstacles in preserving the shelf life, safety, and quality of its products [1]. These issues are made worse by the expectation that the world's population will increase to 9.7 billion people by 2050 and the growing demand for ready-to-eat food, which is expected to reach over \$486 billion globally in 2023 [2,3]. Food packaging has historically acted as a passive barrier to ease distribution and stop physical contamination [4]. Nonetheless, modern demands necessitate packaging that can actively engage with the product and its surroundings to prevent microbial development, reduce deterioration, and preserve the food's sensory qualities [5]. This concept is known as active packaging.

Synthetic plastic packaging is still commonly used because it is inexpensive, lightweight, and simple

to handle [6]. Nevertheless, a number of restrictions decrease its efficacy. For instance, plastic packaging represents more than 36% of total global plastic use [6], with relatively high oxygen permeability (100 - 150  $\text{cm}^3 \cdot \text{mm} / \text{m}^2 \cdot \text{day} \cdot \text{atm}$  for polyethylene) and risks of chemical migration above 70 °C [7]. Another major weakness is the lack of antimicrobial and antioxidant properties [8]. This makes it necessary to directly add preservatives to food goods, which may result in negative health effects and customer backlash.

As science progresses, nanotechnology has become a creative way to enhance packaging performance [9]. Packaging can have its mechanical, barrier, and functional qualities improved without compromising its flexibility or transparency by using nanoscale materials [10,11]. Graphene oxide (GO) is one of the materials that has gained attention

throughout the past 20 years [12]. GO is a two-dimensional graphene derivative containing oxygen functional groups (–OH, epoxy, –COOH) that facilitate dispersion in polymers and chemical modification [12,13].

The special qualities of GO make it a desirable option for active packaging. It has been demonstrated that adding GO to the polymer matrix improves tensile strength and tear resistance [13]. Experimental data show that incorporating 0.5% GO into chitosan increases elongation at break from 9.2% - 20.7% (+124%) and toughness from 1.7 - 5.4 MJ/m<sup>3</sup> (+216%), while reducing water vapor permeability from  $4.23 \times 10^{-11}$  -  $2.21 \times 10^{-11}$  g·m/m<sup>2</sup>·s·Pa [14]. In PBAT films, 1% GO lowers oxygen permeability from 378 - 113 cm<sup>3</sup>·mm/m<sup>2</sup>·day·atm, equivalent to a 70.1% reduction [15]. Furthermore, GO-based films can reduce *Salmonella* and *E. coli* colony counts by 99.9% within 24 h [16].

Functionally, GO demonstrates antimicrobial activity via oxidative stress induction, cell membrane disruption, and biomolecule interactions [17]. Moreover, it protects food items from lipid oxidation because of its antioxidant ability to scavenge free radicals [18]. Recent innovations also show that GO-coated paper packaging can improve tensile strength from 28 MPa to 42 MPa (+50%), provide oil and water resistance without PFAS, and remain compostable [19]. Additionally, the layered GO structure enhances barrier qualities against oxygen, water vapor, and other gases, which is crucial for prolonging shelf life [20].

The use of GO in food packaging still raises concerns about its toxicity and safety, despite its potential [21]. Studies report that GO exposure above 50 µg/mL can induce oxidative stress and cytotoxicity in mammalian cell cultures [22]. Therefore, before GO is extensively used, safety requirements, regulatory considerations, and thorough toxicological analyses are required. Production costs remain high (\$100 - 200 per gram in the research market), and industrial-scale manufacturing technologies are limited [12].

This review article aims to summarize the potential and latest developments regarding the use of graphene oxide as a main component in active food packaging. The focus of the discussion includes the fundamental characteristics of GO, the working mechanism in improving the functional properties of

packaging, practical applications in various food systems, challenges related to safety and technological limitations, and future research prospects. It is intended that by offering a thorough analysis, this paper will be able to track the course of GO development as a novel, sustainable, and safe material in the food packaging sector and offer scientific insight.

### Data collection method

The data for this review were collected through a comprehensive search of peer-reviewed literature, books, and authoritative reports related to graphene oxide (GO) and food packaging applications. Major scientific databases, including Scopus, Web of Science, ScienceDirect, and PubMed, were systematically explored using relevant keywords such as “graphene oxide,” “active packaging,” “nanocomposites,” “antimicrobial activity,” and “barrier properties.” The search primarily focused on publications between 2000 and 2025 to ensure both foundational concepts and the latest developments were considered. Studies were selected based on their relevance to the physicochemical properties, antimicrobial and antioxidant activities, safety and toxicity assessments, as well as practical applications of GO in food packaging systems. Reference lists of retrieved papers were also screened to identify additional relevant sources. Only English-language publications were included, and no original experiments were conducted. Instead, this review synthesizes existing evidence to provide a critical, accurate, and up-to-date overview of GO’s potential as a multifunctional material for active food packaging.

### Properties and characteristics of graphene oxide

Understanding the properties and characteristics of GO is an important basis for assessing its potential as an active packaging material. GO has a unique structure in the form of thin sheets with functional oxygen groups that provide a large surface area and high reactivity. Various synthesis methods, such as the Hummers method and its modifications, allow for the production of GO with different qualities according to application needs. The functional advantages of GO, including mechanical strength, thermal stability, barrier properties against gases and water vapor, and biocompatibility, make it superior to many other

nanocomposite materials and pure graphene. Quantitatively, GO-based films have reported tensile and modulus gains in the order of 30% - 200% alongside OTR/WVTR decreases of 40% - 80% depending on matrix and loading, supporting its role as a multifunctional enhancer in active packaging [14,15]

### **Chemical and physical structure of GO**

Graphene Oxide (GO), a derivative of graphene, is characterized by its unusual structure as a thin sheet with a thickness of only one layer of carbon atoms that ranges from nanometers to micrometers [23]. Chemically, graphene oxide (GO) is created by oxidizing graphene to produce a variety of oxygen functional groups on its surface, including carboxyl ( $-\text{COOH}$ ), epoxy ( $-\text{O}-$ ), and hydroxyl ( $-\text{OH}$ ). These groups are dispersed over the sheet's edges and basal plane [24]. The oxygen group creates new features that are distinct from those of pure graphene by altering the electrical character from pure  $\text{sp}^2$  hybridization to a combination of  $\text{sp}^2 - \text{sp}^3$  [25].

Physically, GO has a very large specific surface area, generally reaching hundreds of square meters per gram, so it is able to provide many active sites for interaction with other molecules, either through hydrogen bonds, electrostatic interactions, or covalent bonds after modification [26]. It is simple to combine GO sheets with other polymers to create nanocomposites because of their thinness, flexibility, transparency, and outstanding thermal stability [27]. Its hydrophilic nature allows GO to be well dispersed in water-based media, in contrast to pure graphene which tends to be hydrophobic [28]. GO is exceptional in enhancing mechanical qualities, barrier resistance to gases and water vapor, and adding functionality to active packaging systems because of its thin atomic structure, reactive oxygen groups, and wide surface area [29]. Typical aqueous surface areas measured by adsorption methods fall in the "hundreds of  $\text{m}^2 \cdot \text{g}^{-1}$ " range, consistent with extensive interfacial reactivity relevant to food-contact matrices [26].

### **GO synthesis method**

In principle, GO synthesis is accomplished by oxidizing graphite to create graphene sheets with functional oxygen groups [30]. Numerous techniques have been developed since the 19<sup>th</sup> century, such as the

Staudenmaier method (1898) and the Brodie method (1859), which use potassium chlorate ( $\text{KClO}_3$ ) in nitric acid ( $\text{HNO}_3$ ) or other strong acid combinations [31]. The use of these processes is becoming less common despite their ability to produce GO with a high oxidation level since they emit harmful gases ( $\text{ClO}_2$  and  $\text{NO}_2$ ) and provide serious safety hazards [18].

The Hummers method (1958), which combines concentrated sulfuric acid ( $\text{H}_2\text{SO}_4$ ), potassium permanganate ( $\text{KMnO}_4$ ), and sodium nitrate ( $\text{NaNO}_3$ ), is the most commonly used technique to date [32]. This oxidation procedure yields GO with a consistent functional oxygen group content and is comparatively safer and more effective than the prior technique [20]. The usage of  $\text{NaNO}_3$  results in the production of hazardous gases ( $\text{NO}_x$ ), and the method's shortcoming is the possibility of creating environmentally dangerous chemical waste [18].

The Modified Hummers Method, a variant that reduces harmful gas emissions by either eliminating  $\text{NaNO}_3$  or substituting it with another oxidizer, was created in order to get around these restrictions [33]. Additionally, some modifications employ phosphoric acid ( $\text{H}_3\text{PO}_4$ ) and sulfuric acid ( $\text{H}_2\text{SO}_4$ ), which improves the homogeneity of the products, increases the degree of graphite oxidation, and lowers the risk of danger during the process [34]. An alternative method involves using ultrasonication to hasten the exfoliation of oxidized graphite into GO sheets that are thinner and more evenly distributed [35].

Recent studies are pointing to environmentally benign alternatives to wet chemistry-based procedures, such as oxidation techniques based on ozone, hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), or even electrochemical techniques, which oxidize graphite in an electrolyte medium using electric current [36]. These methods could lessen the impact on the environment, provide products with more regulated oxidation levels, and employ fewer dangerous chemicals. Notably, electrolytic "green" approaches have demonstrated oxidation and delamination on a seconds-timescale, highlighting a route to scalable and lower-impact production compared with legacy wet chemistry [36].

The goals of the application greatly influence the GO synthesis process selection. A process that can provide GO with high stability, good dispersion, and no harmful residues is crucial for food packaging

requirements [37]. As a result, the adaptation of the Hummers method and the environmentally friendly approach are deemed more pertinent since they may maximize product quality while enhancing the production process's sustainability and safety [33].

### Functional properties

GO is a great option for active packaging applications because of its many useful qualities. From the perspective of mechanical qualities, GO can be added to the polymer matrix to improve tear resistance, elastic modulus, and tensile strength [38]. This is because GO has a huge surface area and reactive functional groups are distributed throughout it, allowing for strong interactions with the polymer chains and the formation of a more stable composite network [39]. Enhancing these mechanical characteristics is crucial to creating packaging that can withstand pressure, impact, and deformation while being transported and stored [40].

Regarding thermal characteristics, GO in polymers can improve thermal durability and reduce packaging materials' rate of thermal deterioration [41]. The glass transition temperature ( $T_g$ ) and degradation temperature rise as a result of the functional oxygen groups in GO acting as hydrogen bonding sites or intermolecular interactions that limit the polymer chain's motion [42]. This feature helps preserve the integrity of the packaging during storage and throughout high-temperature food processing procedures [43]. Typical  $T_g/T_d$  shifts of 5 - 30 °C have been reported in GO-reinforced polymer matrices, indicating improved thermo-mechanical stability under processing conditions [41,42].

Furthermore, GO performs better in barrier characteristics. The dense, non-porous layered structure of GO creates a longer and more tortuous diffusion path for gas molecules and water vapor [44]. The transfer rate of oxygen, carbon dioxide, and water vapor can therefore be considerably decreased by adding GO to polymers [45]. This characteristic is

essential for prolonging the shelf life of food items since it can inhibit changes in sensory quality, moisture loss, and fat oxidation [46]. Across PVC, PVA, PLA, and natural-polymer systems, OTR/WVTR reductions of 40% - 80% are common at sub-percent loadings or thin coatings, consistent with tortuous-path diffusion models [45].

From the standpoint of biocompatibility, GO may find utility in food packaging systems, particularly if it is modified with safe polymers or biomaterials and utilized in small amounts [47]. Though there is currently little information on long-term safety, a number of studies have demonstrated that GO can interact with cells without having a major harmful impact [48-50]. Thus, the biocompatibility of GO remains a research emphasis, especially when considering the possibility of particle migration into food.

### Comparison with graphene and other nanocomposite materials

GO differs from other nanocomposite materials and pure graphene due to a variety of features. It is commonly known that pure graphene has exceptional mechanical strength in addition to extremely high electrical and thermal conductivity [51]. However, graphene's hydrophobic properties limit its ability to disperse in polar polymers and water-based media, making its usage in food packaging systems less than ideal [52]. Conversely, GO's functional oxygen groups increase its hydrophilicity and facilitate its dispersion in a variety of polymer matrices, including biopolymers like polylactic acid, starch, and chitosan [53]. This characteristic enables stronger interactions through covalent and hydrogen bonding as well as the creation of more homogenous composites [54]. **Table 1** presents a comparison between GO, pure graphene, nanoclay, nanosilver, and titanium dioxide ( $TiO_2$ ) based on their main characteristics, advantages, limitations, and potential applications in active food packaging.

**Table 1** Comparison of GO with other nanocomposite materials in active packaging applications.

Material	Main characteristics	Superiority	Limitations	Potential in active packaging
Graphene oxide (GO)	2D sheet, hydrophilic, and functional oxygen groups (–OH, –COOH, –O–)	Multifunctional (barrier, mechanical, antimicrobial, and antioxidant), easy to disperse, and can be modified	High production costs, toxicity issues, and unclear regulations	Highly prospective and multifunctional platform for active packaging
Pure graphene	2D sheet, hydrophobic, and high conductivity	Superior mechanical strength and electrical/thermal conductivity	Difficult to disperse in polar polymers and lacks active functionality	Less relevant for food and more suitable for electronic sensors
Nanoclay	Layered structure, hydrophilic, and compatible with polymers	Improves barrier properties against gas and water vapor, is inexpensive and widely available	Does not have antimicrobial/antioxidant activity	Good as a barrier filler, but not an active agent
Nanosilver (AgNPs)	Metal nanoparticles and high biological activity	Highly effective as a broad spectrum antimicrobial agent	Issues of toxicity to humans and the environment and high costs	Relevant, but needs strict regulation
Titanium dioxide (TiO <sub>2</sub> )	Semiconductor and photocatalytic	Antimicrobial activity and organic degradation under UV	Limited effectiveness without UV light and potential toxicity of nanoparticles	Limited application and suitable for packaging with light exposure

GO exhibits advantages in terms of multifunctionality when compared to other nanocomposite materials, including TiO<sub>2</sub>, nanoclay, and nanosilver [55]. Although nanoclay is frequently utilized to enhance gas and moisture barrier qualities, it has little antibacterial or antioxidant action [56]. Nanosilver is known to be effective as an antimicrobial agent, but is often associated with issues of toxicity and high costs [57]. TiO<sub>2</sub> is more frequently employed as a photocatalytic agent to break down organic molecules and microorganisms, although exposure to UV light is crucial to its action [58]. In this situation, GO can offer multiple benefits simultaneously, including enhanced mechanical qualities, barriers, and active protection via antioxidant and antibacterial capabilities [59]. Practically, GO-polymer films often deliver simultaneous barrier cuts of 50% and  $\geq 1$ -log microbial reductions without external stimuli, whereas TiO<sub>2</sub>

systems typically require UV/visible activation to reach comparable antimicrobial outcomes [58,59].

The potential for further modification of GO is another benefit as compared to traditional nanocomposite materials. GO's functional oxygen groups can serve as reaction sites for the immobilization of bioactive substances like enzymes, essential oils, or natural antioxidants, allowing the packaging's active qualities to be tailored to the requirements of certain food items [60]. As a result, GO serves as a multipurpose platform that can enhance product safety and quality in a comprehensive way, in addition to acting as a reinforcing filler [61].

However, it should be noted that pure graphene still excels in terms of electrical and thermal conductivity, which makes it more suitable for high-precision electronic or sensor applications [62]. Furthermore, GO's toxicity issue has not been

completely addressed, therefore more research is required to guarantee that its safety is on par with or superior to that of nanosilver and TiO<sub>2</sub> in the context of food applications. This is particularly relevant given documented dose- and size-dependent effects *in vitro* and *in vivo*, underscoring the need for migration-aligned exposure limits in food-contact scenarios [21,22].

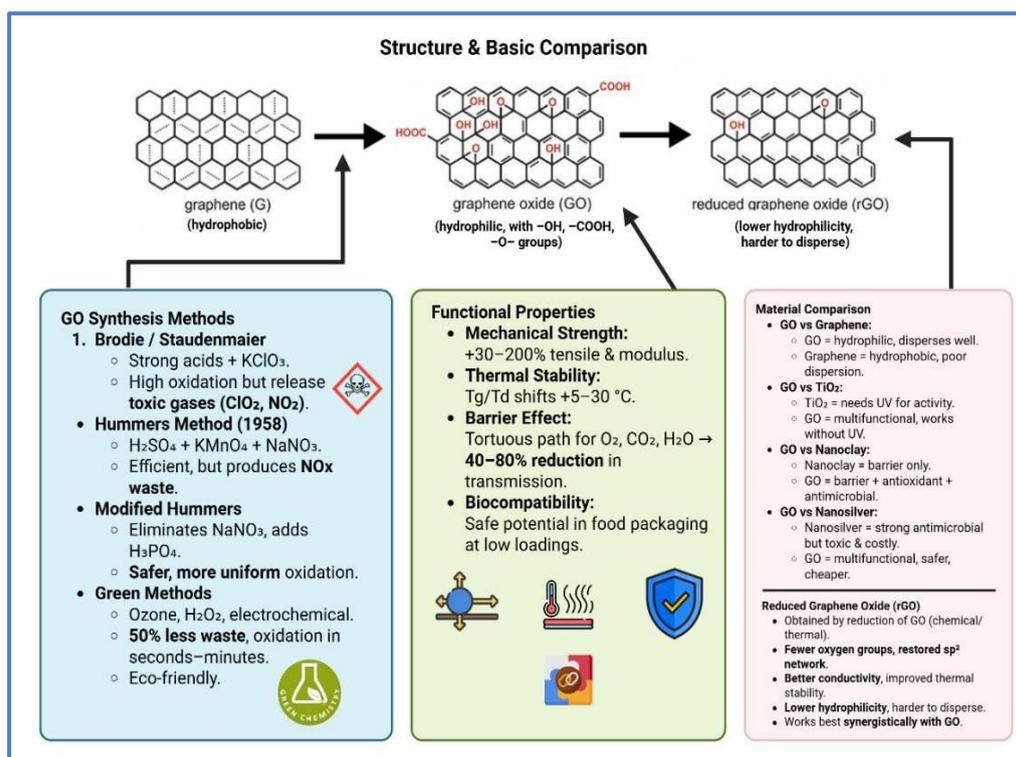
### Reduced graphene oxide (rGO)

In addition to GO, reduced graphene oxide (rGO) has also been investigated as a complementary material in packaging applications. rGO is obtained by chemical or thermal reduction of GO, which decreases the number of oxygen-containing groups and partially restores the conjugated sp<sup>2</sup> network [60,61]. This structural change improves its electrical conductivity and barrier properties, but also reduces its hydrophilicity, making dispersion in aqueous or polar

polymer systems more challenging [62].

Several studies highlight that rGO can enhance the thermal resistance and antioxidant performance of polymer nanocomposites, supporting its role in improving the stability of packaged foods [63]. However, like GO, rGO raises toxicological considerations, as its reduced surface polarity and higher hydrophobicity may influence migration potential and cellular responses [64,65].

Overall, rGO demonstrates promising functionalities, especially when combined with GO to balance dispersion, bioactivity, and structural reinforcement, offering a synergistic pathway for the development of multifunctional food packaging materials [66]. **Figure 1** shows structure, synthesis methods, functional properties, and material comparisons of graphene oxide (GO) and related materials.



**Figure 1** Structure, synthesis methods, functional properties, and material comparisons of graphene oxide (GO) and related materials.

### GO mechanism in active packaging

The mechanism of action of Graphene Oxide (GO) in active packaging involves various synergistic

functions that support the improvement of food quality and safety. GO not only acts as an antimicrobial agent through cell membrane damage and induction of

oxidative stress, but also functions as an antioxidant with the ability to capture free radicals and inhibit lipid oxidation. In addition, the layered structure of GO provides effective barrier properties against the diffusion of oxygen, water vapor, and other gases, thereby slowing the process of food degradation. This advantage is further strengthened by the ability of GO to interact with polymers, forming stable and functional nanocomposites, for example with PLA, PVA, or chitosan.

#### **Antimicrobial activity**

GO has been shown to exhibit antibacterial activity against a variety of fungi and bacteria, both Gram-positive and Gram-negative [63]. The primary process that compromises the integrity of microbial cells is complex and involves both chemical and physical interactions [64]. Physically, bacterial cells can have thin, sharp GO sheets adhere to their surface, which can then “cut” the membrane (a phenomenon known as the nanoknife effect) [65]. This process results in intracellular contents leaking out, membrane permeability increasing, and cell wall degradation [66]. Furthermore, GO’s enormous surface area enables it to wrap bacteria, interfering with the exchange of gasses and nutrients necessary for cell viability [67].

As far as chemistry is concerned, the oxygen groups in GO contribute to the production of Reactive Oxygen Species (ROS), including hydroxyl and superoxide radiation [68]. These ROS have the ability to cause oxidative stress in microbial cells, which can harm proteins, nucleic acids, and membrane lipids [69]. This causes the bacterial metabolism to deteriorate until it dies, DNA replication to be hindered, and essential cell activities to be disturbed [70]. Additionally, a number of studies demonstrate that GO can directly interact with intracellular proteins and DNA via  $\pi$ - $\pi$  interactions and hydrogen bonding, which enhances its antibacterial properties [71-73].

The antimicrobial effectiveness of GO is influenced by various factors, including concentration, sheet size, oxidation level, and the type of target microorganism [63]. Since Gram-negative bacteria have thinner cell walls than Gram-positive bacteria, they are typically more vulnerable [74]. Experimental results show that GO at concentrations of 0.25 - 1.0 mg/mL can reduce bacterial viability by 60% - 90%,

with stronger inhibition against *E. coli* compared to *S. aureus* [63,74,75]. GO provides a multimodal approach to microbial control through a combined mechanism of membrane damage, ROS induction, and biomolecular interactions [75]. As such, it is very applicable for use in active food packaging to increase product safety and shelf life.

#### **Antioxidant activity**

In addition to its antibacterial properties, GO exhibits antioxidant activity, which is crucial for reducing oxidative food degradation [76]. Lipid oxidation is one of the main causes of food quality decline, because it produces volatile compounds that cause rancidity, reduce nutritional content, and affect the sensory properties of the product [77]. Functional oxygen groups like hydroxyl, epoxy, and carboxyl found in GO enable interaction with free radicals and reactive oxygen species (ROS) via a radical scavenging process [78]. Therefore, reactive compounds that have the potential to start oxidative chain reactions can be neutralized by GO [79].

The capacity of GO’s surface to stabilize radicals through hydrogen bonding and  $\pi$ - $\pi$  interactions is also linked to its antioxidant function [76]. The large GO sheets allow for electron distribution that can delocalize radicals, thereby reducing their reactivity [80]. This characteristic is highly advantageous in food systems since it preserves the stability of oxidation-sensitive natural colors, proteins, and lipids [81]. The effectiveness of GO antioxidants can be influenced by the oxidation level of the material and its particle size [82]. Greater scavenging action is typically seen by GO with a high oxygen group content, whereas a smaller sheet size expands the region of contact with target molecules [83]. For example, GO samples with higher oxidation degrees demonstrated DPPH radical scavenging activity of up to 65% - 75%, compared with < 40% in partially reduced forms [82,83]. GO has also been shown to have synergistic effects with bioactive substances like polyphenols or essential oils, strengthening protection against oxidation [84].

#### **Barrier properties**

GO incorporation into polymer matrices is a crucial tactic for creating active packaging

nanocomposites with enhanced mechanical, barrier, and biofunctional qualities [85]. GO contains oxygen functional groups (hydroxyl, epoxy, and carboxyl) that, when chemically modified, can interact strongly with polymers through covalent bonds, hydrogen bonds, and electrostatic interactions [86]. As a result of this interaction, GO and the polymer are more compatible, which keeps GO sheets from clumping together and guarantees uniform mating [87].

Since the oxygen groups of GO and the amino groups of chitosan form strong hydrogen bonds, it has been demonstrated that GO enhances the mechanical and barrier qualities of natural polymers like chitosan [88]. The addition of GO can increase thermal resistance while decreasing the oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) in biodegradable synthetic polymers like polylactic acid (PLA) and polyvinyl alcohol (PVA) [89]. Reductions in OTR and WVTR ranging from 40% to over 70% have been documented in PLA/GO and PVA/GO composites at  $\leq 1$  wt% GO loading [88,89]. As a result, GO is a multipurpose additive that enhances physical qualities while also adding biological activities like antioxidant and antibacterial [29,37].

Furthermore, GO can serve as a platform for the binding or encapsulation of additional bioactive substances, including enzymes, polyphenols, and essential oils [90]. GO strengthens the impact of active packaging on food by acting as a carrier that releases active components in a regulated manner [59].

According to recent research, GO combined with chitosan loaded with essential oils results in packaging that has improved stability, broad antibacterial activity, and strong barrier qualities [91].

Since inadequate GO dispersion or high concentration can decrease mechanical characteristics and even increase permeability, optimizing the composition and manufacturing process of nanocomposites is still difficult [92]. Thus, in order to create nanocomposites with the best possible performance, the surface modification method of GO and the application of suitable mixing procedures (solution casting, melt mixing, or electrospinning) are essential [93].

### Interaction with polymers

GO has been extensively researched as a reinforcement in polymer matrices to create high-performing active packaging nanocomposites [94]. The benefit of GO is that it contains oxygen functional groups that offer high chemical reactivity, like carboxyl, epoxy, and hydroxyl [95]. These groups allow strong interactions with various types of polymers, both natural and synthetic, through hydrogen bonds, electrostatic interactions, and covalent bonds after surface modification [73]. The GO sheets may be uniformly distributed throughout the matrix thanks to these interactions, which also make GO more compatible with the polymer and inhibit agglomeration [96]. **Table 2** shows a comparison of GO interactions with several important polymers in the development of active packaging.

**Table 2** Interaction of GO with polymers in active packaging nanocomposite systems.

Types of polymers	Interaction mechanism with GO	Resulting trait improvements	Potential applications
Chitosan (natural)	Hydrogen bonds between the amino group ( $-NH_2$ ) of chitosan and the carboxyl group ( $-COOH$ ) of GO	<ul style="list-style-type: none"> <li>• Stronger mechanical properties</li> <li>• Increased barrier against <math>O_2</math> and <math>H_2O</math> - Broader antimicrobial activity (chitosan + GO synergy)</li> </ul>	Biodegradable antimicrobial packaging for fresh meat and processed fish products
Polylactic Acid (PLA)	Hydrogen interactions and covalent bonds (after GO modification)	<ul style="list-style-type: none"> <li>• Improved thermal resistance</li> <li>• Reduced OTR and WVTR</li> <li>• Increased mechanical stability</li> </ul>	Active packaging for dry or semi-wet products
Polyvinyl Alcohol (PVA)	Homogeneous dispersion through	<ul style="list-style-type: none"> <li>• Maintains film transparency</li> <li>• Improves gas and moisture barrier</li> </ul>	Biodegradable thin films and edible

	hydrogen bonds and electrostatic interactions	<ul style="list-style-type: none"> <li>• Increases film durability</li> </ul>	coatings
Chitosan/GO + essential oil	GO as a carrier, releases bioactive compounds in a controlled manner	<ul style="list-style-type: none"> <li>• Synergistic antimicrobial effect</li> <li>• Improved film stability</li> <li>• Increased antioxidant potential</li> </ul>	Active packaging for perishable foods (fruit, fresh vegetables, and ready-to-eat products)

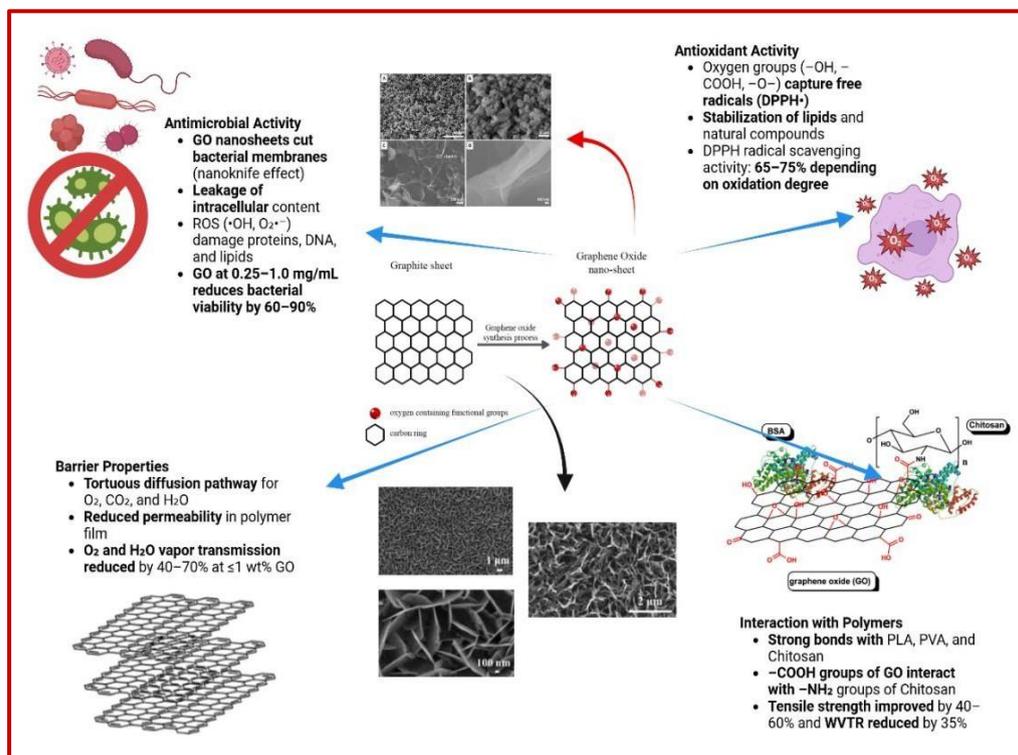
The presence of amino groups ( $-NH_2$ ) in natural polymers like chitosan interacts with carboxyl groups ( $-COOH$ ) in GO to produce stable hydrogen bonds [97]. It has been demonstrated that this combination enhances the mechanical qualities of chitosan films while fortifying their ability to block water vapor and oxygen [98]. For example, tensile strength of chitosan films improved by 40% - 60% and WVTR decreased by 35% upon GO addition at low concentrations [97,98]. Furthermore, the combination of GO's biological activity and chitosan's inherent antibacterial qualities produces a material with a wider range of microbial suppression [99].

In the meanwhile, GO is added to biodegradable synthetic polymers like polylactic acid (PLA) and polyvinyl alcohol (PVA) to increase mechanical qualities, heat resistance, and the rate at which oxygen and water vapor are transmitted [100]. This effect happens as a result of the tortuous diffusion routes formed by the GO sheets orientated in the matrix, which impede the entrance of moisture and gas molecules [101].

GO can be used to immobilize bioactive substances in addition to enhancing their physical characteristics [102]. According to a number of studies, GO can bind enzymes, polyphenols, or essential oils to its surface before releasing them gradually [103-105].

The ability to directly release antioxidants or antimicrobials onto the food surface expands the usefulness of active packaging [106]. For instance, it has been demonstrated that chitosan-GO composites containing essential oils exhibit superior film persistence and more inhibitory efficacy against harmful bacteria when compared to single polymers [107].

However, variables like concentration, mixing technique, and GO oxidation state have a significant impact on how well GO interacts with polymers [108]. A concentration that is too high may result in agglomeration, decrease homogeneity, and potentially impair the film's mechanical qualities [109]. Above 2 wt% GO loading, some studies report decreases in tensile strength and elongation, highlighting the importance of maintaining an optimal range ( $\leq 1$  wt%) for packaging performance [108,109]. Therefore, the qualities of the polymer and the goals of the application must be taken into consideration when choosing processing methods such solution casting, melt compounding, or electrospinning [110]. **Figure 2** explains the multifunctional roles of graphene oxide (GO) in active food packaging, including antimicrobial, antioxidant, barrier, and polymer interaction properties.



**Figure 2** Multifunctional mechanisms of graphene oxide in active food packaging.

### GO application in food packaging system

The application of GO in food packaging systems is not limited to a single function, but encompasses a variety of complementary, innovative approaches. GO can be utilized as a component of polymer nanocomposites to improve mechanical and barrier properties, as well as as an active layer (coating) on packaging surfaces to provide additional protection against microbial contamination and oxidation. Furthermore, the development of GO-based smart sensor technology opens up new opportunities for real-time food freshness detection. Numerous case studies on various products such as meat, milk, fruit, and processed foods further strengthen the evidence of GO's potential as a multifunctional material in supporting modern packaging systems that are safe, efficient, and sustainable.

### GO in polymer nanocomposites to improve mechanical and barrier properties

GO has become one of the most promising additives in polymer nanocomposite formulations for active packaging applications [111]. Strong interactions with the polymer matrix are made possible by GO's lamellar structure, which has a huge surface

area and oxygen functional groups. Surface modification can result in covalent bonds, hydrogen bonds, or electrostatic bonds [112]. Increased mechanical qualities, including tensile strength, elastic modulus, and tear resistance, are the outcome of good GO dispersion in polymers [113]. This happens as a result of the GO sheets' function as "nanofillers," which reinforce the polymer network by transferring stress [114].

The addition of GO has been shown to be successful in improving the barrier qualities of polymers against oxygen, water vapor, and other small molecules in addition to fortifying their mechanical qualities [115]. The orientation of the GO sheets in the matrix creates a tortuous diffusion path, thus slowing down gas penetration [116]. Numerous GO-modified polymer systems, such as polylactic acid (PLA), polyvinyl alcohol (PVA), and chitosan, have been shown to exhibit decreases in both oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) [117]. For instance, PLA/GO composites with 0.5 - 1 wt% GO loading reported tensile strength increases of 40% - 60% and OTR reductions of 45% - 70%, directly contributing to shelf-life extension of packaged foods [115-117]. GO-based nanocomposites can thereby

greatly increase the shelf life of food items by preventing moisture loss, aerobic bacteria growth, and lipid degradation [19].

The effectiveness of GO in improving mechanical and barrier properties is greatly influenced by factors such as concentration, sheet size, oxidation level, and nanocomposite processing method [118]. A concentration that is too high could cause agglomeration, which would actually degrade the film's qualities, while a concentration that is too low might not have any discernible impact [119]. Consequently, formulation optimization plays a crucial role in the industrial use of GO.

### **GO as an active layer (coating) on the surface of the packaging**

An inventive method of enhancing the functionality and performance of packaging materials is the application of GO as an active layer (coating) on the food packaging surface [120]. GO can be applied on polymer or paper substrates directly or via layer-by-layer assembling, dipping, and spraying methods [121]. Since GO is hydrophilic and made of functional oxygen groups (hydroxyl, epoxy, and carboxyl), it may adhere strongly to a variety of surfaces and produce a stable, uniform coating [122].

The GO layer has a dual function, namely as a physical barrier and a bioactive agent. GO functions as a barrier that slows down food deterioration from oxidation and moisture loss by decreasing the permeability of oxygen, water vapor, and other gases through a convoluted diffusion pathway mechanism [123]. However, GO also has antioxidant and antibacterial properties. The microbial inhibitory impact of GO sheets on food surfaces is enhanced by their capacity to generate ROS, yet thin and sharp GO sheets can harm bacterial cell membranes [124,125]. Studies have shown that chitosan-GO coatings reduced *E. coli* and *S. aureus* populations by 1-2 log CFU within 24 - 48 h, while lowering OTR by 50% compared with uncoated controls [124-126].

According to a number of studies, GO-based coatings on cellulose, chitosan, and polylactic acid (PLA) films can increase the shelf life of dairy, meat, and fruit [43,47]. GO can also be utilized as a platform to load other bioactive substances, including polyphenols or essential oils, which are then released

under controlled conditions [126]. Therefore, the GO layer actively contributes to preserving the food's chemical stability and microbiological safety in addition to acting as a passive barrier [127].

However, the possibility of particle migration into food, toxicity concerns, and regulatory restrictions present difficulties when using GO as a coating [79]. Therefore, prior to industrial deployment, GO surface modification techniques, layer thickness optimization, and comprehensive safety testing are needed.

### **GO in smart sensor for food freshness detection**

Contemporary food packaging technology is being developed with an eye on both providing immediate information about the product's condition and serving protective purposes [128]. Given this, GO has enormous promise as the primary component of intelligent packaging that detects the freshness of food [129]. GO has a large specific surface area, electrical conductivity that can be enhanced by reduction, and functional oxygen groups that enable selective interaction with different volatile compounds or metabolites that are created during the breakdown process [130].

The fundamental idea behind the use of GO in smart sensors is that when GO interacts with target molecules, such as ammonia, hydrogen sulfide, or biogenic amines (putrescine, cadaverine) generated by rotten food, its electrical or optical characteristics change [131]. These alterations can be translated into quantifiable indications, such as fluorescence responses, color shifts, or variations in electrical resistance [132]. As a result, GO-based sensors can offer digital or visual food quality indicators in real time [133].

GO has also been shown to enhance the sensor's sensitivity and selectivity when combined with other polymers or support materials like chitosan, cellulose, or polyaniline [134]. Numerous investigations have demonstrated that GO nanocomposite films, which react quickly to volatile amine concentrations, can be employed as freshness indicators for meat or fish [129,135,136]. In practical terms, GO-based sensors have detected volatile amines at concentrations as low as 10 - 50 ppm within minutes, allowing freshness monitoring of fish and poultry during cold storage [135

- 137]. The development of multipurpose sensor systems that can concurrently detect many freshness parameters is also made possible by combination with pH-sensitive dyes or specific enzymes [137].

From a practical perspective, GO-based sensors can be developed in the form of labels or strips that are attached directly to the packaging, so that consumers and producers can monitor the freshness of the product without opening the packaging [138]. GO is a strong contender for the creation of a new generation of smart packaging because of these benefits, which not only preserve food quality but also make supply chain data more transparent [139].

### Case study

The efficacy of using GO in active packaging to prolong shelf life and preserve quality has been evaluated on a variety of food goods. It has been demonstrated that adding GO to chitosan or polylactic acid (PLA)-based films in fresh meat products inhibits the growth of harmful bacteria like *Staphylococcus aureus* and *Escherichia coli* while slowing down the rate of lipid oxidation [140]. In beef and poultry packaging, GO-based films reduced bacterial counts by 2 log CFU and delayed rancidity for 3 - 5 additional days compared to control films [140]. The meat's vivid red color will be more stable and the onset of rotten odor will be postponed during cold storage. **Table 3** summarizes various applications of GO in active packaging in animal and plant food products.

**Table 3** Application of GO in active packaging in various food products.

Food products	GO-based packaging system	Main effects	Reference
Fresh meat	Chitosan/PLA + GO nanocomposite film	<ul style="list-style-type: none"> <li>• Inhibits the growth of <i>E. coli</i> and <i>S. aureus</i></li> <li>• Reduces lipid oxidation</li> <li>• Maintains a fresh red color</li> <li>• Extends refrigerated shelf life</li> </ul>	[140]
Milk and milk products	Biodegradable polymer film + GO	<ul style="list-style-type: none"> <li>• Reduces the growth of spoilage microbes</li> <li>• Maintains protein stability</li> <li>• Reduces pH changes</li> <li>• Improves product safety</li> </ul>	[141]
Fruits and vegetables	Thin layer of GO on PVA or cellulose	<ul style="list-style-type: none"> <li>• Reduces respiration</li> <li>• Suppresses moisture loss</li> <li>• Slows wilting</li> <li>• Prevents enzymatic browning</li> </ul>	[142]
Fish and seafood	Biopolymer + GO ± essential oil composite film	<ul style="list-style-type: none"> <li>• Inhibits the formation of biogenic amines (putrescine, cadaverine, and TMA)</li> <li>• Suppresses microbial growth</li> <li>• Increases antioxidant activity</li> </ul>	[143]

It has been claimed that GO nanocomposite films in dairy products and their derivatives can decrease pH fluctuations that often result from uncontrolled fermentation, preserve protein integrity, and slow the growth of spoilage bacteria [141]. Fresh cheese stored in GO-PLA films showed pH stability within  $\pm 0.2$  units and microbial load reductions of 1.5 log CFU over 10 days compared with controls [141]. This demonstrates that GO is successful in reducing

secondary contamination, which frequently occurs in fresh cheese and liquid milk products.

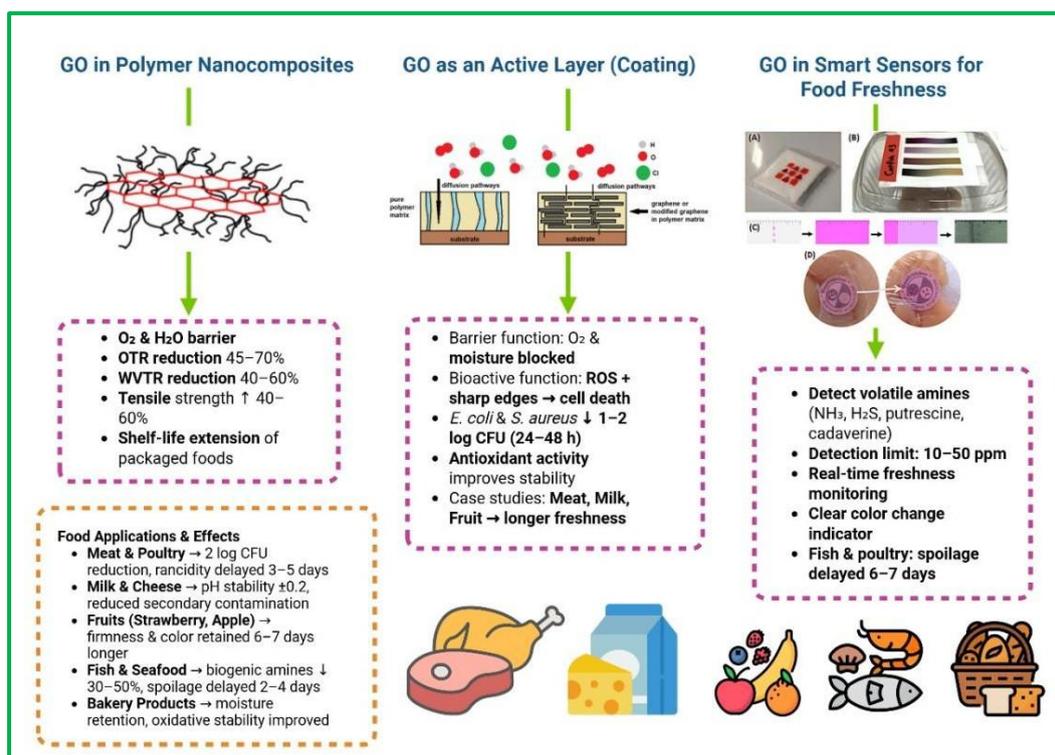
The withering process of fresh fruits and vegetables has been slowed by applying a thin layer of GO over polyvinyl alcohol (PVA) or cellulose films, which has been shown to lower the respiration rate and moisture loss [142]. Furthermore, GO's oxygen barrier qualities prevent enzymatic browning and preserve the fruit's sensory appeal while it is being stored [46]. For

example, strawberries and apples coated with GO–PVA films retained firmness and color up to 6–7 days longer than uncoated samples [142].

In the meantime, GO-based packaging effectively inhibits the production of biogenic amines, such as putrescine and cadaverine, which are the primary markers of spoiling in fish and fisheries goods [143]. GO coatings reduced amine accumulation by 30%–50% in stored fish fillets, delaying spoilage onset for 2–4 days compared to conventional films [143,144]. GO

even offers double protection when combined with other bioactive substances, including essential oils, which have complementary antioxidant and antibacterial properties [144].

**Figure 3** summarizes the applications of graphene oxide (GO) in modern food packaging, encompassing its role as a nanofiller in polymer composites, as an active surface coating, and as a component of intelligent sensor systems.



**Figure 3** Multifunctional applications of graphene oxide (GO) in food packaging systems through nanocomposites, active coatings, and smart sensors.

### Safety and toxicity of GO

The safety and toxicity of graphene oxide (GO) are crucial issues that must be studied before its widespread implementation in food packaging. Evaluating the potential migration of GO particles into food matrices is the first step in assessing consumer exposure risks. Furthermore, various toxicological studies in cellular and animal models have been conducted to understand the biological impacts of GO, including bioaccumulation, oxidative stress, and immune responses. Consequently, increased attention

to regulations and safety standards for nanotechnology in food packaging is essential to ensure that the use of GO is not only effective in extending shelf life but also safe for human health and the environment.

### Evaluation of the potential for GO migration into food

A key component of determining whether GO can be used commercially is evaluating the possibility of GO migrating from packaging materials into food [29]. Migration is defined as the movement of material

components from the packaging to the food matrix, which in nanomaterials can pose more complex risks than conventional additives [11]. This is because of GO's special characteristics, which include its high surface area, nanometer-scale particle size, and oxygen functional groups, which increase its reactivity with molecules in the environment [145].

Factors that influence GO migration include food composition, storage conditions, and packaging material characteristics [47]. For instance, the nature of hydrophobic interactions makes high-fat products more prone to particle release [146]. It has also been demonstrated that temperature and storage duration are important factors; rising temperatures can hasten polymer degradation and raise the possibility of GO release [147]. Furthermore, the stability of GO is also influenced by the kind of polymer that is utilized as a binding matrix; natural polymers, like chitosan, exhibit more stable bindings than some synthetic polymers [148].

As advised by the European Food Safety Authority (EFSA), migration studies are typically conducted using common food simulants, such as vegetable oils, 3% acetic acid, or 10% ethanol, to simulate various food kinds [149]. The existence of GO following contact with simulants is analyzed using sophisticated methods such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Raman Spectroscopy, and Transmission Electron Microscopy (TEM) [150]. Recent migration trials showed GO release levels generally below 10 µg/L in aqueous simulants and < 50 µg/kg in fatty food models, remaining under most provisional safety thresholds [151-153]. According to the findings of a number of early investigations, GO migrates at a comparatively

slow rate, particularly when the particles are uniformly distributed and firmly bonded inside the polymer network [151-153]. Nonetheless, there is still a chance of release, especially in cases of severe storage conditions or mechanical damage to the film.

Any migrating GO particles may be biologically hazardous from the standpoint of food safety since they may interact with bodily systems, induce oxidative stress, or possibly have inflammatory consequences [154]. Therefore, migration data should be combined with *in vitro* and *in vivo* toxicology test results to develop a comprehensive risk assessment [155]. This kind of approach is important so that a Specific Migration Limit (SML) can be set specifically for GO, as has been the case for conventional additives in food packaging [156].

#### Toxicological data on test cells and animals

Many toxicological investigations of GO in test animals and cellular models have been carried out to determine the safety of its uses, including possible food packaging. Numerous investigations have demonstrated that GO can have cytotoxic effects at the cellular level that vary according to particle size, concentration, and exposure duration. For instance, GO exposure to cultures of liver and mammalian intestinal epithelial cells causes the apoptotic pathway to be activated, cell membranes to rupture, and an increase in ROS generation [157]. These effects typically intensify at high concentrations (> 50 µg/mL), but GO typically exhibits negligible or even undetectable cytotoxicity at low exposures [158]. **Table 4** summarizes the research results regarding the toxicity effects of GO on various test models, both *in vitro* (cellular) and *in vivo* (experimental animals)

**Table 4** Toxic effects of GO on cell models and test animals.

Test model	GO exposure conditions	Key findings	Reference
Intestinal epithelial cells ( <i>in vitro</i> )	10 - 100 µg/mL at 24 - 48 h	<ul style="list-style-type: none"> <li>• Increased ROS</li> <li>• Membrane damage</li> <li>• Apoptosis activation</li> <li>• Cytotoxicity increased with dose.</li> </ul>	[157]
Mammalian liver cells ( <i>in vitro</i> )	> 50 µg/mL at 24 h	<ul style="list-style-type: none"> <li>• Oxidative stress</li> <li>• Mitochondrial dysfunction</li> <li>• Changes in gene expression</li> </ul>	[158]
Cultured cells with	10 - 100 µg/mL at 24 - 72 h	<ul style="list-style-type: none"> <li>• Reduced cytotoxicity</li> </ul>	[159,160]

Test model	GO exposure conditions	Key findings	Reference
modified GO (PEG/Chitosan)		<ul style="list-style-type: none"> <li>• Increased dispersion stability</li> <li>• Minimal membrane interactions</li> </ul>	
Rats (oral and subchronic)	5 - 50 mg/kg BW at 28 days	<ul style="list-style-type: none"> <li>• GO accumulation in liver, kidney, and spleen</li> <li>• Mild histopathological changes</li> <li>• Oxidative stress biomarkers were increased</li> </ul>	[161]
Rats (inhalation)	GO aerosol 0.1 - 1 mg/m <sup>3</sup> for 5 days	<ul style="list-style-type: none"> <li>• Acute pulmonary inflammation</li> <li>• Response decreases after recovery</li> <li>• Particle size &lt; 100 nm → stronger immune response</li> </ul>	[162]
Mice (oral and low dose)	1 - 5 mg/kg BW at 14 days	<ul style="list-style-type: none"> <li>• No significant toxic effects;</li> <li>• Minimal hematologic changes</li> <li>• Relatively safe at low doses</li> </ul>	[163]

Furthermore, the control of gene expression and enzyme function may be impacted by GO interactions with intracellular proteins and DNA, which may result in chronic oxidative stress [22]. However, a number of studies found that by improving dispersion stability and lowering direct interactions with cell membranes, surface modification of GO with biocompatible polymers (such as chitosan or polyethylene glycol) could lower the degree of cytotoxicity [159,160].

Research findings also reveal different biological reactions in test animal models. Subchronic oral GO intake in rats and mice typically causes tissue buildup and particle distribution to the liver, kidney, and spleen [161]. Among the impacts found were slight hematological alterations, elevated oxidative stress indicators, and modest liver histological alterations. In mice, tests of GO inhalation revealed an inflammatory response in the lungs, albeit these symptoms gradually subsided after exposure was terminated. It is interesting to note that smaller GO particles (less than 100 nm) have been shown in multiple studies to induce a higher immunological response than micrometer-sized particles [162].

According to the scientific data now available, GO toxicity is generally dose- and size-dependent and significantly impacted by the exposure route. At oral doses below 10 mg/kg/day, no significant toxic effects were observed, whereas repeated exposures above 50 - 100 mg/kg/day showed histological and biochemical alterations in rodent models [163]. Low levels of oral

intake are generally safe, but long-term accumulation or chronic exposure remains a risk [163]. Therefore, a thorough toxicological assessment that considers realistic conditions of particle migration into food products, including long-term safety studies, is required before GO may be widely used in food packaging.

#### **Regulations and safety standards for nanotechnology materials for food packaging**

Strict regulations are needed to protect consumer safety as nanotechnology advances, including the usage of GO in food packaging. Nanomaterials are distinct from traditional materials due to their reactive qualities, high surface area, and extremely small particle size, which can be hazardous to human health and the environment [164]. International regulatory organizations have therefore started to develop particular guidelines to guarantee that these substances are safe for use in the food supply chain.

The European Food Safety Authority (EFSA) has released particular recommendations for evaluating the safety of nanomaterials used in food and food packaging in Europe [165]. This rule highlights the significance of *in vitro* and *in vivo* toxicity investigations, comprehensive material characterization (size, shape, surface area, and chemical characteristics), and specific migration limits (SML) testing. Furthermore, before being put on the market, any new products based on nanotechnology must be

approved by the Novel Food Regulation or Food Contact products Regulation (EC No. 1935/2004) process [166].

The Food and Drug Administration (FDA) in the US similarly promotes a risk-based strategy when it comes to nanomaterials. The FDA mandates manufacturers to submit thorough safety data, including details on migration, consumer exposure, and toxicological test findings, but it does not have any particular requirements for graphene oxide [167]. According to the Food Contact Notification Program, assessment is necessary if nanoparticles are added to polymers [168].

Through the Joint Expert Committee on Food Additives (JECFA), FAO/WHO has advised that bioaccumulation, biological interactions, and environmental effects be taken into account when studying nanomaterials in food and packaging on a worldwide scale [169]. International frameworks stress the precautionary principle, which states that any new item must be extensively examined before being permitted into circulation, even though there isn't a single standard that specifically governs GO.

The primary obstacles in the context of consumer safety are the absence of long-term toxicological evidence and the limits of conventional techniques for the detection and measurement of GO migration in food [170]. As a result, a lot of researchers stress the necessity of developing reliable analytical techniques, harmonizing international laws, and establishing precise exposure limits for carbon-based nanomaterials like graphene oxide.

### **Advantages and limitations of GO as active packaging**

The unusual physicochemical features of GO make it a viable material for active packaging systems. One of GO's primary benefits is its versatility, which includes its ability to prevent oxidative deterioration, stop the growth of germs, and potentially be used as a part of an intelligent packaging system that tracks the quality of food [79]. Furthermore, GO exhibits excellent compatibility with a wide range of synthetic and natural polymers, including polylactic acid, polyethylene, and chitosan and cellulose, allowing for the production of nanocomposite films with improved

functional qualities [171]. For example, the incorporation of 1 - 2 wt% GO into PLA or PVA films has been shown to increase tensile strength by up to 30% and reduce oxygen transmission rate (OTR) by 25% - 40%, thereby prolonging food shelf life by several days under refrigerated conditions [43]. GO may prolong food's shelf life more efficiently than traditional materials because of its outstanding mechanical and barrier qualities, which include high tensile strength, low gas permeability, and the capacity to reinforce polymer structures [43].

However, there are still a lot of restrictions for using GO in food packaging. One of these is the comparatively high manufacturing costs brought on by the intricate synthesis and purifying procedure, which prevents its use on an industrial scale [121]. Conventional chemical oxidation routes (e.g., Hummers method) cost nearly 2 - 3 times more per gram compared to nanoclay or nanosilver fillers, making large-scale production economically challenging. Furthermore, the possible migration of GO particles into food, which can result in harmful biological effects including inflammation and oxidative stress, raises serious concerns about toxicity [29]. Another drawback is the lack of detailed and precise rules governing the use of GO in food packaging, including recommendations for long-term toxicological testing and safe migration limits. The long-term stability issue is still problematic since environmental elements including temperature, humidity, and light exposure can alter GO's characteristics, potentially compromising the packaging's efficacy and safety [172].

Therefore, even though GO has many benefits as an active packaging material, more focused study is still needed to fully implement it. The main focus should be on developing more economical production methods, clarifying toxicity mechanisms, and establishing clear regulations and safety standards. Toxicology, materials science, and regulatory policy must be integrated in a multidisciplinary manner for GO to be broadly used while maintaining consumer protection and food safety.

### **Prospects and directions for future research**

Although various studies have demonstrated the potential of GO in improving the functional properties

of active packaging, future development directions still require a comprehensive strategic approach. One of the primary goals is to create safer, more affordable, and ecologically friendly GO synthesis techniques because traditional manufacturing methods still employ toxic chemicals that may have negative effects on the environment [145]. For instance, green electrochemical oxidation methods have been reported to reduce chemical waste by > 50% and lower production costs by nearly 20% - 30% compared to the Modified Hummers Method [173]. It is anticipated that a green synthesis-based strategy utilizing eco-friendly electrochemical techniques and natural oxidants will lower expenses while improving production sustainability [173].

Concerns about GO migration into the food matrix are also quite significant. Research is therefore focused on improving the formulation of polymer-GO nanocomposites using techniques like surface functionalization or protective coverings made of biomaterials to reduce particle release. Studies show that coating GO films with chitosan or alginate can decrease migration levels by nearly 40% - 60% compared to uncoated GO composites, while maintaining barrier performance. Combining GO with renewable biomaterials like chitosan, polylactic acid (PLA), or polyhydroxyalkanoates (PHA) also creates the possibility of developing packaging based on nanocomposite that is not only useful but also biodegradable and environmentally benign [174].

GO-based smart packaging is emerging as a promising research field in keeping with the innovation trend in the food business. For instance, GO can be used as a food quality sensor to detect volatile gases, humidity, or signs of product freshness due to its electrical conductivity and great sensitivity to chemical changes [138]. Recent prototypes of GO-based amine sensors demonstrated detection limits as low as 1 - 5 ppm for cadaverine and putrescine, which are spoilage markers in fish and meat. This innovation promotes a safer and more effective food distribution system in addition to raising the added value of packaging.

Lastly, safety and regulatory concerns are inextricably linked to efforts to utilize GO as food packaging. Future investigations should focus on thorough toxicological analyses, which should include GO exposure's long-term effects on biological systems

and an assessment of the environmental impact following use. Comprehensive chronic exposure studies ( $\geq 90$  days) are still scarce, with most available data limited to short-term models, underscoring the need for standardized long-term evaluations. The study's findings will give international regulatory bodies a solid scientific foundation on which to build rules and regulations pertaining to the use of GO in food packaging.

## Conclusions

This review highlights graphene oxide (GO) as a promising multifunctional material for active food packaging due to its large surface area, reactive oxygen groups, and good compatibility with polymers. These properties improve mechanical strength, thermal stability, and barrier performance while also providing antimicrobial and antioxidant functions that extend shelf life and maintain food quality. Advances in synthesis, particularly green and electrochemical methods, offer safer and more sustainable pathways for production, and applications extend beyond nanocomposites and coatings to smart packaging with real-time freshness sensing.

Despite these advantages, challenges remain regarding migration, toxicity, long-term stability, and high production costs. Future research should focus on safer and more economical synthesis, comprehensive toxicological evaluations, and strategies to ensure stable dispersion in biodegradable polymers. Stronger regulatory frameworks are also required to set clear safety standards. With these developments, GO has strong potential to become a safe, effective, and sustainable material for next-generation food packaging.

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#### Declaration of Generative AI in Scientific Writing

The authors declare that no generative AI tools were used in the writing or preparation of this manuscript.

#### CRedit Author Statement

**B.P.P.** and **A.R.K.** led the conceptualization and initial drafting of the manuscript. **D.A.A.K.** and **W.Y.** contributed to literature gathering and data interpretation, while **B.W.K.W.** and **I.F.M.** assisted in analytical refinement. **A.O.A.**, **R.Z.A.**, and **A.N.M.A.** supported critical review and content consolidation. **M.S.**, **L.L.**, **N.R.A.**, and **F.D.A.** contributed to manuscript editing and improvement. **M.R.F.H.** provided administrative and technical assistance, and **I.M.** supervised the overall preparation of the review. All authors contributed substantially to the development of this paper and approved the final version.

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