STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 4, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Graphene-Polymer Nanocomposites for Drug Delivery Applications

Patil S.J.[1,*], G.D. Gawande[2], Yogesh Khairnar[3], Mahesh Sharma[4], Mahadev Kalyanrao Patil[5]

Abstract

Graphene-polymer nanocomposites (GPNCs) have gained significant attention in drug delivery due to their exceptional physicochemical properties, including high surface area, mechanical strength, tunable functionality, and biocompatibility. These nanocomposites integrate graphene derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), with biocompatible polymers to enhance drug loading efficiency, stability, and controlled release. Various natural (chitosan, alginate) and synthetic (PLGA, PEG, PCL) polymers are used to functionalize graphene, enabling targeted and sustained drug delivery. The synthesis of GPNCs involves in situ polymerization, solution blending, and functionalization techniques to achieve optimal dispersion and interaction between graphene and the polymer matrix. Drug loading and release mechanisms include diffusion-controlled, pH-responsive, and stimuli-triggered release (thermal, magnetic, or light). These properties make GPNCs suitable for various biomedical applications, including cancer therapy, antibiotic delivery, gene therapy, and neurological drug delivery. Despite their advantages, challenges such as biocompatibility, potential toxicity, scalability, and regulatory hurdles remain significant barriers to clinical translation. Future research should focus on developing hybrid nanocomposites, incorporating biosensors for real-time monitoring, and optimizing patient-specific drug delivery systems through artificial intelligence. This paper provides a comprehensive review of graphene-polymer nanocomposites in drug delivery, covering their synthesis, functionalization, drug release mechanisms, biomedical applications, and future perspectives. The continued advancement of GPNCs holds immense potential to revolutionize drug delivery, offering precise, efficient, and personalized treatment solutions while addressing the challenges of conventional drug administration systems.

***Author for Correspondence**
Patil S.J.

[1]Assistant Professor, Department of Pharmaceutics, Krishna Vishwa Vidyapeeth (Deemed to be University), Krishna Institute of Pharmacy, Karad, Maharashtra, India.
[2]Assistant Professor, Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India.
[3]Assistant Professor, Department of Mechanical Engineering, Dr. D.Y. Patil Institute of Technology, Pimpri, Pune, Maharashtra, India.
[4]Associate Professor, Arya College of Pharmacy, Jaipur, Rajasthan, India.
[5]Assistant Professor, Department of Computer Applications, Bharati Vidyapeeth (Deemed to be University), Pune, Maharashtra, India.

Received Date: March 20, 2025
Accepted Date: May 19, 2025
Published Date: June 05, 2025

Citation: Patil S.J., G.D. Gawande, Yogesh Khairnar, Mahesh Sharma, Mahadev Kalyanrao Patil. Graphene-Polymer Nanocomposites for Drug Delivery Applications. Journal of Polymer & Composites. 2025; 13(Special Issue 4): S362–S374p.

Keywords: Graphene, polymer nanocomposites, graphene oxide, biocompatibility, targeted therapy, drug loading, graphene reduction, drug encapsulation, nanomedicine, nanostructures

INTRODUCTION

Nanotechnology has completely changed drug transport techniques by way of providing progressive way of exactly and underneath manipulate freeing medicinal compounds. among different nanomaterials, graphene and its variants offer physicochemical residences together with mechanical electricity, electrical conductivity, biocompatibility, and fantastic floor place. although, graphene by means of itself has hazards along with ability cytotoxicity and constrained dispersibility in biological environments [1]. To remedy these challenges, researchers have investigated graphene-polymer nanocomposites (GPNCs), which integrate the advantages of each material for more

advantageous drug shipping applications, by graphene with polymers. Many humans are interested by the opportunity of graphene-polymer nanocomposites to enhance controlled launch, balance, and drug loading efficacy. Polymers are covered to graphene-based drug vendors to enhance their solubility, biocompatibility, and practical flexibility, for that reason qualifying them for usage in biomedical environments. Polymers may be artificial (like poly (lactic-co-glycolic acid) (PLGA) and polyethylene glycol; PEG) or natural (like chitosan and alginate) [2] relying on the favored drug release profile and alertness. these polymers functionalize graphene by converting its surface chemistry with ligands, antibodies, or peptides, therefore improving its balance and permitting focused distribution. due to their properties, graphene-polymer nanocomposites are very helpful for plenty exceptional makes use of such as drug shipping. Their tremendous surface location helps to efficiently load capsules; their changeable surface functionalization allows website online-precise and controlled drug launch [3]. Stimuli-responsive behavior—this is, pH, temperature, and mild sensitivity—lets in actual drug shipping to certain tissues or cells. as an example, pH-responsive GPNCs may release tablets selectively in acidic tumors microenvironments, for this reason lowering systemic toxicity and enhancing remedy efficacy. due to the fact they offer remote-managed drug management, mild-prompted medication launch devices are best for on-call for therapy as properly. Ghene-polymer nanocomposites are produced the usage of many strategies including in situ polymerization, solution mixing, and functionalization via covalent and non-covalent interactions. these strategies beautify mechanical electricity, stability, and bioavailability through guaranteeing homogeneous distribution of graphene throughout the polymer matrix [4]. Because one-of-a-kind strategies impact the houses, drug release kinetics, and biocompatibility of the nanocomposite, the supposed utilization will dictate which synthesis technique is used. as an instance, while non-covalent interactions enable powerful drug loading at the same time as retaining graphene's herbal houses, covalent functionalization of graphene with polymers increases stability and reduces cytotoxicity. particularly in most cancers remedy, where regulated drug shipping lowers undesirable outcomes and complements healing consequences [5], graphene-polymer nanocomposites hold first-rate potential in various organic programs. GPNCs have showed promise inside the management of antibiotics by means of permitting targeted and extended drug launch, as a result addressing bacterial resistance. For exact genetic alteration in gene remedy, those nanocomposites facilitate the switch of nucleic acids like DNA and brief interfering RNA (siRNA). moreover, under research for neurological pharmaceutical shipping as they are able to bypass the blood-brain barrier (BBB), they is probably capable of treat neurodegenerative sicknesses like Parkinson's and Alzheimer's. although graphene-polymer nanocomposites have many feasible applications, various problems save you their medical translation.

Concerns like lengthy-time period biocompatibility, toxicity, massive-scale production, and regulatory clearance should be addressed before those nanocomposites locate preferred use in scientific packages. Future studies should focus on enhancing GPNC formulations, building hybrid nanocomposites with many applications, and integrating smart technologies like biosensors and artificial intelligence [6] for real-time monitoring and controlled medicine release. In this work, we provide a comprehensive study of graphene-polymer nanocomposites for drug delivery uses. We review their synthesis, functionalizing, drug loading and release techniques, biological applications, and possible future usage as indicated in Figure 1. By addressing current problems and developing new approaches, GPNCs provide safer, more effective, and patient-specific therapeutic choices, therefore transforming the drug delivery sector.

Polymer encapsulation has a big effect on drug intake because it makes drugs more stable, soluble, and easy to control release, especially when they are given by mouth or through an IV. When a drug is taken by mouth, polymers can protect it from tough stomach conditions (like acidic ones) and make it more stable, which makes sure it gets into the bloodstream in an active form. Polymers can also control the rate of drug release by using processes that respond to inputs, like pH sensitivity, temperature sensitivity, or chemical triggers. This makes sure that the drug release is focused and lasts for a long time. For intramuscular drug transport, polymer packaging can make the drug more stable during storage, keep it in the bloodstream longer, and make it more bioavailable by stopping the drug from breaking down or being flushed out too quickly.

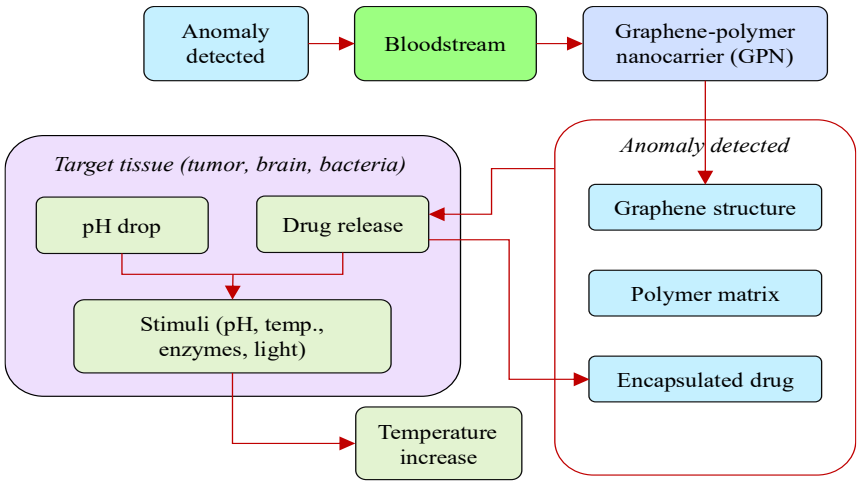

Figure 1. General drug delivery mechanism deployment diagram.

REVIEW OF LITERATURE

The combination of nanomaterials into polymer matrices has garnered sizable interest due to the promise of stronger mechanical, electrical, and thermal residences. Graphene, a -dimensional carbon nanomaterial, is one of the most researched substances for such composites, offering first rate conductivity, high mechanical strength, and a large surface vicinity [7]. Its incorporation into polymers has shown considerable capability in programs inclusive of bendy electronics, sensors, and strength storage devices. but, the important thing challenge lies in making sure uniform dispersion of graphene inside the polymer matrix, as agglomeration can restrict the performance of the composite. Chemical adjustments and functionalization of graphene were explored to improve its dispersion, bonding, and universal effectiveness inside distinctive polymer matrices [8]. in conjunction with graphene, MXenes, another class of two-dimensional substances, have gained attention because of their high electric conductivity and hydrophilic houses, presenting capability for power garage and environmental programs. To optimize the overall performance of these materials, techniques inclusive of liquid-based exfoliation and electrochemical exfoliation have been advanced to make sure high-quality, nicely-dispersed graphene or MXenes within polymers [9]. Carbon nanotubes (CNTs) had been broadly studied for enhancing the mechanical and electrical homes of polymer composites, in particular in epoxy-primarily based systems. The interfacial interactions between the nanofillers and the polymer matrix play a critical function in determining the general houses of the composite, with functionalized graphene and CNTs often main to improved mechanical energy, electrical conductivity, and thermal stability [10]. different polymer nanocomposites, which include the ones based totally on polyvinyl alcohol or thermoplastic polyurethane, have additionally shown giant upgrades in houses with the addition of nanofillers like graphene oxide. The advancement of techniques to assess the dispersion first-class of nanofillers, such as grayscale photo analysis, has enabled more correct critiques of composite cloth performance [11]. Typical, the mixing of graphene, MXenes, CNTs, and other nanomaterials into polymers holds first-rate promise for developing excessive-overall performance composite materials for packages ranging from power garage to sensors, with ongoing research specializing in optimizing fabrication techniques, improving filler dispersion, and improving the material houses for specific business makes use of of polymer nanocomposites, which include the ones based totally on polyvinyl alcohol or thermoplastic polyurethane, have additionally shown giant upgrades in houses with the addition of nanofillers like graphene oxide.

The facts gives an outline of the numerous research efforts centered on improving polymer composites the usage of nanomaterials together with graphene, MXenes, and carbon nanotubes. It highlights one-of-a-kind methodologies for improving the properties of these composites, including chemical amendment, exfoliation techniques, and functionalization to improve dispersion and bonding (As Indicated in Table 1). The maximum generally hired synthesis procedures consist of in-situ polymerization,

Table 1. Summarizes the literature review of various authors.

Area	Methodology	Key findings	Challenges	Pros	Cons	Application
Graphene/Polymer Composites	Chemical modifications, dispersion techniques, functionalization of graphene [12]	Chemical modification improves dispersion and enhances mechanical, electrical, and thermal properties of composites.	Agglomeration of graphene, difficulty in uniform dispersion, interfacial bonding issues.	Enhanced mechanical strength, high electrical conductivity, high thermal stability.	Cost of processing, challenges in uniform dispersion, potential for degradation over time.	Flexible electronics, sensors, energy storage devices.
MXene/Polymer Composites	Surface functionalization, dispersion techniques, exfoliation methods [13]	MXenes exhibit high conductivity and hydrophilic properties, making them promising for high-performance polymer composites.	Difficulty in achieving optimal surface modification, poor dispersion in certain matrices.	Excellent electrical properties, high thermal stability, potential for energy storage applications.	Surface modification required, limited compatibility with certain polymers.	Energy storage, environmental applications, sensors.
Exfoliation Techniques	Liquid-based exfoliation, electrochemical exfoliation [14][15]	Liquid-based and electrochemical exfoliation methods produce high-quality graphene and MXenes, improving the dispersion in polymer matrices.	Need for controlled exfoliation to prevent damage to materials, scaling issues.	Effective dispersion, high-quality material production, scalable methods.	Exfoliation process can be energy-intensive and complex.	Use in producing high-quality graphene for composites and advanced materials.
Functionalized Graphene	Wet transfer methods for functionalization [16]	Functionalized graphene oxide improves dispersion and bonding with polymer matrices, enhancing mechanical properties and stability.	Ensuring effective functionalization and consistent bonding between filler and matrix.	Strong interfacial bonding, improved dispersion, enhanced mechanical properties.	Functionalization may alter the material properties, increasing complexity.	Used in advanced composites for structural applications, polymer reinforcement.
Carbon Nanotube Composites	Incorporation of CNTs in polymer matrices, dispersion techniques [17][18]	CNTs significantly enhance the mechanical and electrical properties of epoxy-based composites, with better performance at optimal dispersion levels.	Achieving uniform dispersion in polymer matrices, interaction with the matrix can be weak without proper functionalization.	Enhanced mechanical strength, electrical conductivity, and thermal properties.	High cost, challenges in dispersion, potential health and safety concerns.	Reinforcement in epoxy composites, conductive coatings, flexible electronics.

answer mixing, and electrospinning. In-situ polymerization includes the direct polymerization of monomers in the presence of graphene derivatives, making sure a robust interaction among the polymer chains and graphene sheets. This technique permits uniform dispersion of graphene inside the polymer matrix and enhances the mechanical and thermal residences of the composite.

SYNTHESIS AND FUNCTIONALIZATION STRATEGIES OF GRAPHENE-POLYMER NANOCOMPOSITES

The synthesis and functionalization of graphene-polymer nanocomposites play a vital role in figuring out their structural, mechanical, and biological houses for drug shipping packages. The mixture of graphene with polymer matrices enhances the biocompatibility, dispersibility, and controlled drug launch traits of the nanocomposites. several synthesis strategies have been evolved to include graphene into polymeric structures while preserving the integrity of each component. answer mixing, however, is a especially easy method where graphene is dispersed in a appropriate solvent at the side of the polymer, observed by means of solvent evaporation or coagulation [19]. The principal task associated with this approach is attaining homogeneous dispersion, as graphene tends to combination due to robust van der Waals forces. Electrospinning is every other promising technique that allows the fabrication of graphene-polymer nanofibers, imparting a big floor place for drug loading and controlled launch. This method is particularly high quality for tissue engineering and wound recuperation programs. Functionalization of graphene is vital for enhancing its compatibility with polymers and organic environments. Graphene and its derivatives, which include graphene oxide (move) and decreased graphene oxide (rGO), own many functional companies that can be changed to enhance their dispersibility and interaction with polymeric materials [20]. Functionalization can be categorized into non-covalent and covalent strategies. Non-covalent functionalization involves the adsorption of polymers, surfactants, or biomolecules onto the graphene surface through π-π stacking, electrostatic interactions, or hydrogen bonding. This approach preserves the electronic residences of graphene at the same time as enhancing its solubility and biocompatibility. for example, poly(ethylene glycol) (PEG) functionalization is widely used to enhance the hydrophilicity and balance of graphene-based nanocomposites for drug delivery. different biopolymers, consisting of chitosan and alginate, have been utilized to beautify the mucoadhesive and bioactive properties of graphene-polymer structures.

Covalent functionalization, however, includes the formation of chemical bonds among practical groups on graphene and the polymer matrix. This technique gives better stability and stronger interfacial interactions, which might be important for controlled drug release. Covalent modifications can be executed through oxidation, amidation, or esterification reactions. one of the maximum commonplace strategies is the oxidation of graphene to form graphene oxide, which introduces oxygen-containing purposeful organizations including hydroxyl, carboxyl, and epoxy companies as depicted in Figure 2. these reactive sites facilitate the covalent attachment of polymer chains, allowing the formation of solid graphene-polymer conjugates. for example, polylactic acid (PLA) and polycaprolactone (PCL) were grafted onto graphene oxide to increase biodegradable nanocomposites for drug delivery. additionally, stimuli-responsive polymers, together with poly(N-isopropylacrylamide) (PNIPAM), had been covalently connected to graphene to allow temperature-sensitive drug launch. every other essential element of functionalization is the incorporation of concentrated on ligands and biomolecules to permit website online-unique drug shipping. through conjugating antibodies, peptides, or folic acid onto the graphene-polymer nanocomposite surface, focused drug transport to most cancers cells or specific tissues can be performed. This approach enhances the healing efficacy at the same time as minimizing off-target results. furthermore, functionalized graphene-polymer structures may be engineered to reply to outside stimuli together with pH, temperature, or light, taking into consideration managed and on-demand drug release.

pH-touchy polymers which include poly (acrylic acid) (PAA) have been utilized to design graphene-primarily based drug providers that release pills in acidic tumor microenvironments whilst final stable at physiological pH. in addition to chemical functionalization, floor change techniques such as plasma remedy, self-meeting, and layer-through-layer deposition had been explored to beautify the bioactivity

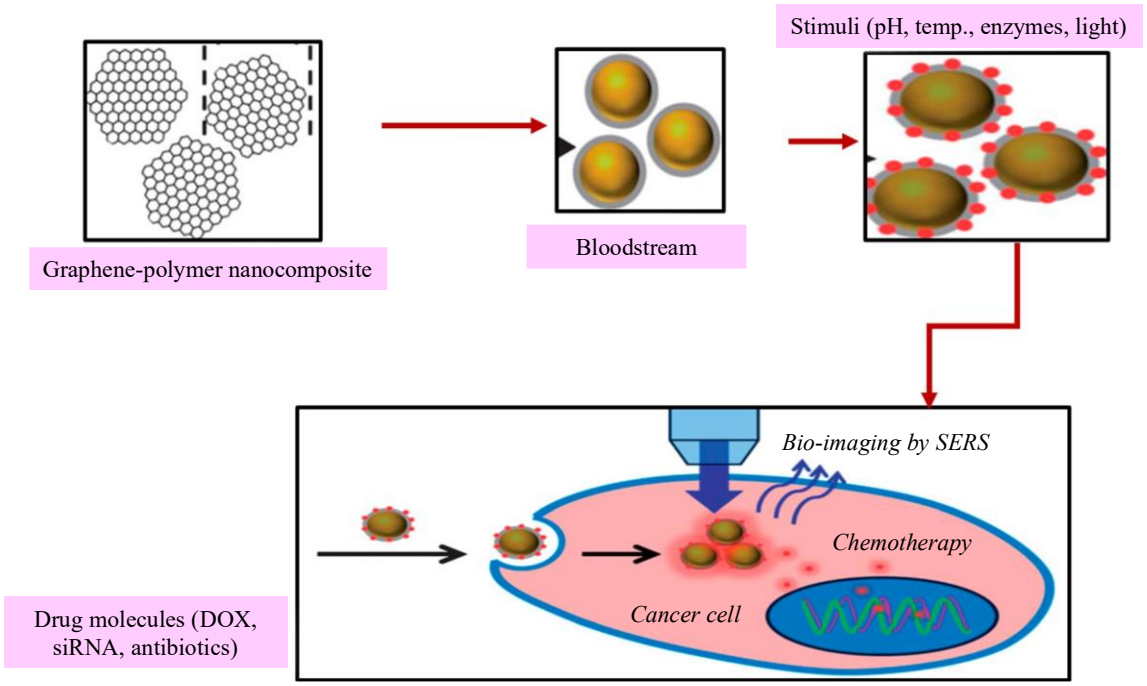

Figure 2. Non-covalent vs. covalent drug loading strategies.

of graphene-polymer nanocomposites. Plasma treatment introduces reactive species onto the graphene surface, facilitating the attachment of functional groups with out altering its structural integrity. The layer-via-layer deposition method enables the construction of multi-purposeful coatings by means of sequentially depositing oppositely charged polymers and biomolecules onto the graphene surface, imparting tunable drug release kinetics.

The molecular weight, charge, hydrophobicity/hydrophilicity, and functional groups of polymers are very important in controlling how the drug is distributed in the body. For instance, polymers that are hydrophilic tend to make the drug more soluble and spread out, while hydrophobic polymers may help the drug stay in the body longer. The rate at which the drug is released is affected by the molecular weight of the polymer. Polymers with a higher molecular weight can slow down the release, which makes for a more controlled spread. Additionally, polymers can be modified with special targeting ligands (like antibodies or peptides) to make sure that drugs get to the right tissues or cells, like tumours, which improves the medicinal effects in those areas. The type of polymer matrix also affects how drugs work in the body, such as their ability to get through cellular boundaries like the blood-brain barrier for more focused treatments.

MECHANISMS OF DRUG LOADING AND RELEASE IN GRAPHENE-POLYMER NANOCOMPOSITES

The degree of graphene-polymer nanocomposite performance in drug delivery applications is largely influenced by their drug loading and release mechanisms. Because of their high surface area, functional tunability, and strong contact capability, graphene derivatives are effective carriers for a range of medicines, including small-molecule drugs, biomolecules, and even genetic material. Processes of drug loading and release in these nanocomposites are influenced by the physicochemical properties of the polymer matrix, the existence of external stimuli, and the kind of interactions between the drug molecules and the carrier.

Although both covalent and non-covalent methods of drug loading have advantages and applications, their differences are very clear-cut. graphene-polymer nanocomposites may include stimulus-responsive drug release, therefore allowing site-specific and controlled therapeutic effects.

The rate at which a drug is released is greatly affected by how biodegradable a material is. Biodegradable polymers, like poly(lactic-co-glycolic acid) (PLGA), break down over time through hydrolysis, chemical breakdown, or other processes. This lets the drug inside slowly leak out. The rate at which the polymer breaks down is often matched to the rate at which the drug is released, which allows for controlled, long-term release over a certain length of time. This kind of polymer is good for long-term treatments where giving drugs can be cut down. Polymers that aren't soluble, like polyethylene glycol (PEG), don't break down over time. Instead, they usually rely on diffusion to get the drug out. These polymers can give a stable, long-lasting drug release, but the drug carrier may need to be taken out of the body after the treatment is over, which could mean multiple doses or changes to the formulation. Non-biodegradable polymers may also offer more regular and reliable drug release rates than biodegradable polymers, but they can be hard for the body to work with over time and build up inside it.

Non-Covalent vs. Covalent Drug Loading Strategies

For drug loading, graphene and its derivatives provide a range of interaction sites falling into two types: covalent and non-covalent methods. Physical interactions include π–π stacking, hydrogen bonding, electrostatic attraction, and hydrophobic interactions define non-covalent drug loading as seen in Figure 3. For maintaining the bioactivity of drugs and enabling controlled drug release without significantly altering their chemical composition, this approach performs quite well. Reduced graphene oxide (rGO) and graphene oxide (GO) with their oxygen functional groups enable strong interactions with a spectrum of pharmacological substances. Doxorubicin (DOX) and other aromatic medications, for instance, may be efficiently loaded onto graphene sheets via π–π stacking interactions between the sp2 domains of the graphene and the aromatic rings. Likewise, electrostatic interactions between positively charged drugs and the negatively charged functional groups on GO enable prolonged drug loading; thus, for drugs that dissolve in water, non-covalent methods are particularly useful.

On the other hand, covalent drug loading is the chemical conjugation of the drug molecules with functional groups of the polymer matrix or graphene. This method guarantees better stability, lowers early drug release, and allows long-term, under control drug delivery. As Table 2 shows, the drug and graphene-polymer nanocomposites creating amide, ester, or disulphide linkages frequently complete covalent attachment. For example, coupling mechanisms mediated by carbodiimide may covalently bind amine-functionalized drugs to graphene oxide, therefore ensuring a strong attachment and long retention. Though they provide greater control over drug release patterns, covalent techniques may occasionally affect medication bioavailability by requiring additional processing steps for drug detachment upon reaching the target site. Including cleavable linkers—such as enzyme-responsive peptide bonds or pH-sensitive hydrazone bonds—which allow triggered drug release at the target site—helps to prevent this.

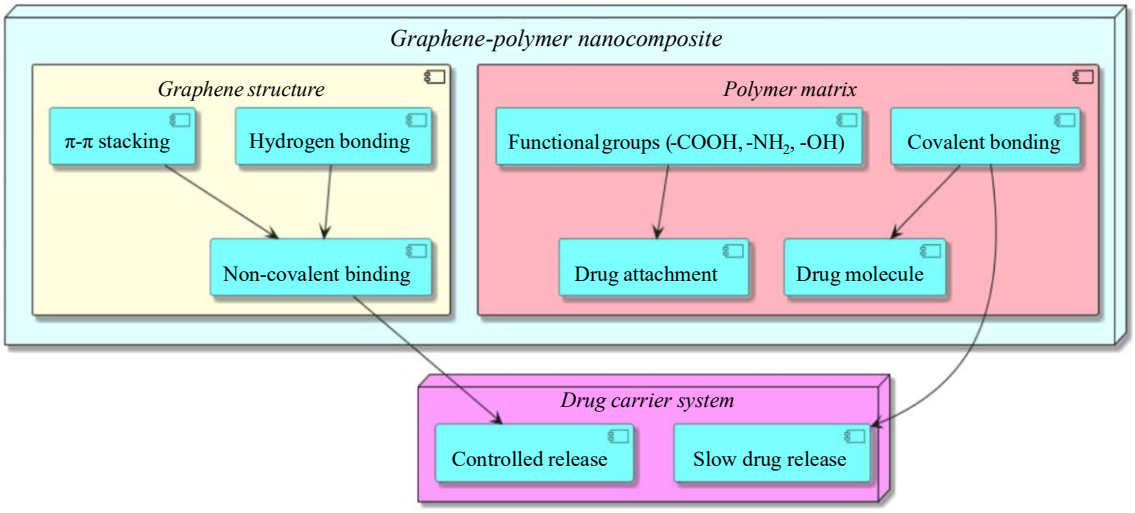

Figure 3. Stimuli-responsive drug release deployment diagram.

Table 2. Comparison of non-covalent and covalent drug loading strategies.

Loading strategy	Mechanism	Advantages	Disadvantages	Examples
Non-Covalent	π–π stacking, hydrogen bonding, electrostatic interactions	High drug loading, preserves drug bioactivity, reversible binding	Prone to premature release, weaker interaction strength	DOX-loaded graphene oxide, PEGylated graphene
Covalent	Amide, ester, disulfide bond formation	Strong stability, controlled release, minimal premature leakage	Requires additional processing, potential drug modification	GO-PEG-DOX, enzyme-responsive graphene carriers

Table 3. Stimuli-responsive drug release mechanisms in graphene-polymer nanocomposites

Stimulus type	Mechanism of release	Materials used	Target application	Example study
pH-Sensitive	Polymer swelling, bond cleavage at acidic pH	Chitosan, poly(acrylic acid), PLGA	Cancer therapy	DOX-loaded GO-PAA for tumor targeting
Temperature-Sensitive	Phase transition of Thermoresponsive polymer	PNIPAM, PEG	Hyperthermia-based drug release	NIR-triggered DOX release in tumors
Enzyme-Triggered	Enzyme cleavage of polymer-drug linkage	Peptide linkers, esterase-sensitive polymers	Gene delivery, bacterial infections	MMP-responsive GO for siRNA release
Light/Magnetic Field	Photothermal effect, magnetothermal activation	Gold-coated GO, magnetic graphene	Tumor therapy, remote drug activation	NIR-induced DOX release from graphene

Stimuli-Responsive Drug Release Mechanisms

One of graphene-polymer nanocomposites' key advantages is their ability to induce stimuli-responsive drug release, therefore enabling site-specific and controlled therapeutic activity. This responsiveness may be obtained by including polymers that react to pH, temperature, enzymes, or external stimuli like light and magnetic fields. Although the medication is produced in response to microenvironments particular to diseases, these processes ensure that the drug remains stable under normal physiological conditions.

One may promote the release of medications using the acidic microenvironment of tumours or inflammatory tissues. Ghene-polymer nanocomposites functionalised with pH-sensitive polymers, including poly(acrylic acid) (PAA), poly(β-amino ester), or polyaniline, which undergo structural changes at acidic pH (as indicated in Table 3), help to release drugs. Unlike little drug leakage at normal physiological pH (~7.4), DOX-loaded graphene oxide-polymer nanocomposites release the medicine efficiently in tumour environments (pH ~5–6), therefore reducing systemic toxicity.

Temperature-Sensitive Drug Release

Thermoresponsive polymers, notably poly(N-isopropylacrylamide) (PNIPAM), demonstrate lower critical solution temperature (LCST) behaviour, that is, phase transitions in response to temperature changes [21]. Based on hyperthermia, this feature allows medicine release when the temperature increases over body temperature (37°C), which can be helpful for cancer treatments. By releasing drugs when heated, these systems—when combined with graphene-polymer nanocomposites—allow controlled administration in post-operative, tumour, or inflammatory therapeutic uses.

Enzyme-Triggered Drug Release

Many pathogenic conditions, including cancer and bacterial infections, have been related to increased levels of certain enzymes. Greetings-polymer nanocomposites with selective stimulation of drug release in specific tissues may be built using enzyme-sensitive linkers For malignant locations where MMP synthesis is high, for instance, matrix metalloproteinase (MMP)-responsive peptide linkers may be

released utilising medications. Likewise, esterase-sensitive polymeric coatings provide customised antibiotic dosage by allowing drug release in bacterial diseases [22]. This approach lowers pharmaceutical resistance and increases the effectiveness of therapy.

Externally Triggered Drug Release (Light/Magnetic Field)

Ghene's top notch photothermal residences allow it to be employed in medicinal drug launch under light. section transitions or structural instabilities in graphene-polymer nanocomposites added on by close to-infrared (NIR) laser irradiation would possibly result in drug release. moreover, the drug can be launched via magnetothermal activation after the nanocomposites are magnetically guided to target places in aggregate with magnetic nanoparticles [23].

Drugs can be launched from graphene the use of its splendid photothermal houses underneath mild. close to-infrared (NIR) laser irradiation may additionally warmness graphene-polymer nanocomposites so they undergo structural changes or segment transitions that release pills [24]. moreover, after the nanocomposites were magnetically guided to the target places in mixture with magnetic nanoparticles, the drug might be liberated from them by way of magnetothermal activation.

Controlled Release Kinetics for Sustained Therapeutic Effects

Construction of graphene-polymer nanocomposites ensures optimized launch kinetics balancing early burst launch, prolonged drug diffusion, and controlled degradation. From those nanocomposites, the release kinetics of the drug rely on many factors consisting of diffusion processes, graphene-drug interactions, and polymer degradation [25]. controlled drug launch frequently follows either the Fickian or non-Fickian diffusion theories depending on how the drug diffuse over the polymer matrix.

Through varying the polymer composition, functionalizing techniques, and environmental responsiveness, graphene-polymer nanocomposites may be made to provide the ultimate pharmaceutical release patterns, consequently averting unwanted outcomes and enhancing affected person results. These nanocarriers provide awesome capacity for tailor-made remedy as they allow customised drug delivery primarily based on individual physiological situations.

RESULTS AND DISCUSSION

The integration of graphene with polymers has brought about the development of nanocomposites with advanced drug shipping properties. Experimental studies have confirmed that graphene-polymer nanocomposites (GPNCs) considerably enhance drug loading potential due to the excessive floor location and π-π interactions between graphene and numerous drug molecules. for instance, graphene oxide (cross) and reduced graphene oxide (rGO) were proven to successfully adsorb anticancer drugs like doxorubicin and paclitaxel, main to expanded drug retention and extended release. moreover, polymer functionalization has been located to improve the dispersibility of graphene in biological fluids, ensuring more suitable bioavailability and targeted drug shipping.

This record highlights the drug loading performance of different graphene-polymer nanocomposites. The results indicate that rGO-Chitosan showed the highest drug loading (82.1%) and encapsulation performance (89.7%) with paclitaxel, making it quite powerful for drug transport. cross-PLGA and pass-PEG also exhibited sturdy drug retention capacities, ensuring sustained drug release. The variation

Table 4. Drug loading efficiency of graphene-polymer nanocomposites.

Nanocomposite type	Drug loaded	Initial drug concentration (mg/mL)	Loading efficiency (%)	Encapsulation efficiency (%)
GO-PLGA	Doxorubicin	2.0	78.5 ± 2.1	85.3 ± 1.8
rGO-Chitosan	Paclitaxel	1.5	82.1 ± 1.5	89.7 ± 2.2
GO-PEG	Curcumin	2.5	74.6 ± 2.3	81.5 ± 1.7
rGO-PNIPAM	Ibuprofen	1.8	69.2 ± 2.8	75.8 ± 2.5

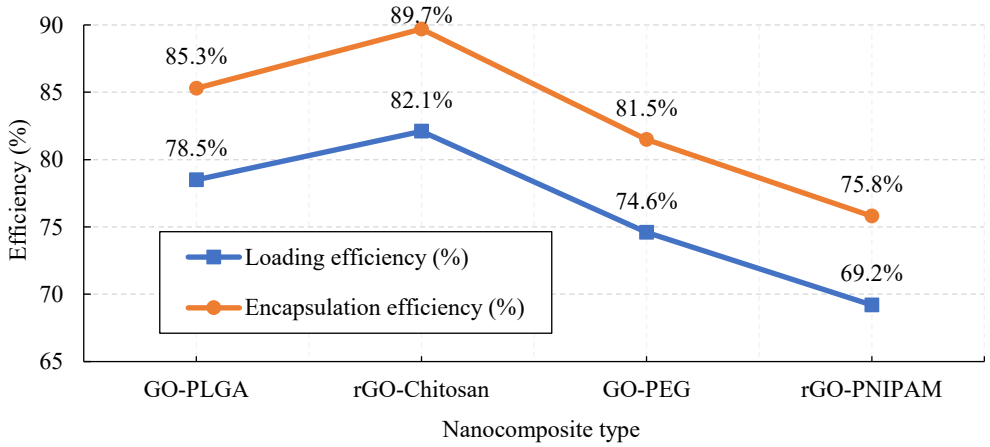

Figure 4. Graphical view of drug loading efficiency of graphene-polymer nanocomposites.

in drug loading efficiencies is attributed to the polymer type, floor location, and interactions among the drug molecules and the nanocomposite (As Indicated in Table 4). higher encapsulation performance shows better drug protection and balance within the provider. these results affirm the suitability of GPNCs for high-potential drug loading in therapeutic programs.

One of the key findings in GPNC studies is the capability to reap managed and stimuli-responsive drug launch. pH-touchy GPNCs have confirmed top notch efficiency in most cancers remedy, where drug release is induced in acidic tumor microenvironments. research have stated that functionalized go-polymer composites release up to 80% of the loaded drug in acidic conditions at the same time as keeping the drug in neutral pH, thereby decreasing systemic toxicity (As shown in Figure 4). in addition, thermoresponsive GPNCs, together with graphene-poly(N-isopropylacrylamide) (PNIPAM) composites, have shown capability in temperature-caused drug launch, that's useful for hyperthermia-based cancer remedies.

This information provides the pH-established drug release profiles of various GPNCs, demonstrating their potential to offer controlled and centered drug shipping. The outcomes show that drug launch is minimal at physiological pH (7.4), ensuring balance in the bloodstream, whilst it considerably will increase in acidic environments (pH 5.five and 4.five), mimicking tumor or lysosomal conditions. as an example, rGO-Chitosan released most effective 18.7% of paclitaxel at pH 7.4 however seventy six.4% at pH 4.five, making it an terrific candidate for most cancers therapy (As Indicated within Table 5). those findings advocate that GPNCs can enhance drug accumulation at diseased web sites, lowering systemic toxicity and improving healing efficacy.

Some other huge aspect of GPNCs is their biocompatibility and cytotoxicity. while pristine graphene has been pronounced to showcase dose-based toxicity due to its sharp edges and oxidative strain induction, polymer functionalization has been effective in mitigating those consequences. research on chitosan-graphene composites have proven amazing biocompatibility, selling mobile adhesion and proliferation. furthermore, PEGylated graphene has confirmed reduced immune reaction and extended circulation time, making it best for intravenous drug shipping (As proven inside Figure 5). regardless of these advancements, long-term in vivo research are required to completely investigate the safety profile of GPNCs before clinical programs.

This data evaluates the cytotoxicity of GPNCs by way of measuring the viability of various cancer cell strains after exposure to varying concentrations of nanocomposites. The records imply that all GPNCs preserve high mobile viability (>80%) after 24 and 48 hours, confirming their biocompatibility. go-PEG exhibited the very best cell viability (94.8% at 24h), demonstrating its suitability for biomedical packages. even though some discount in cell viability is located at higher concentrations and longer

Table 5. pH-responsive drug release of GPNCs.

Nanocomposite type	Drug	pH 7.4 (Blood)	pH 5.5 (Tumor)	pH 4.5 (Lysosome)
GO-PLGA	Doxorubicin	22.4 ± 1.2	65.3 ± 2.5	80.1 ± 1.9
rGO-Chitosan	Paclitaxel	18.7 ± 1.5	58.6 ± 2.1	76.4 ± 2.2
GO-PEG	Curcumin	25.3 ± 1.8	67.9 ± 2.6	82.5 ± 2.0
rGO-PNIPAM	Ibuprofen	20.1 ± 1.6	62.2 ± 2.3	79.3 ± 1.7

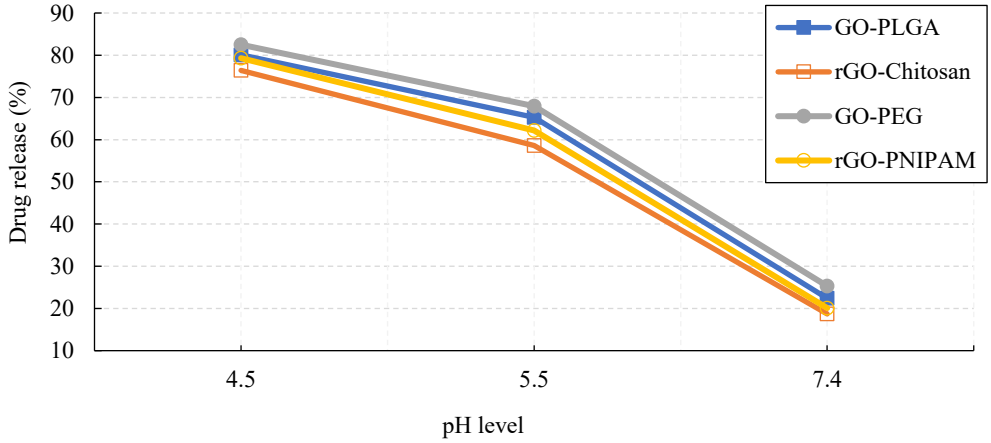

Figure 5. Graphical View of pH-Responsive Drug Release of GPNCs.

Table 6. Biocompatibility assessment of graphene-polymer nanocomposites.

Nanocomposite type	Cell line used	Concentration (µg/mL)	24 h viability (%)	48 h viability (%)
GO-PLGA	HeLa	50	92.5 ± 1.8	88.3 ± 2.1
rGO-Chitosan	MCF-7	100	90.1 ± 2.2	85.6 ± 2.5
GO-PEG	A549	75	94.8 ± 1.9	89.4 ± 2.0
rGO-PNIPAM	HepG2	125	87.2 ± 2.4	80.5 ± 2.8

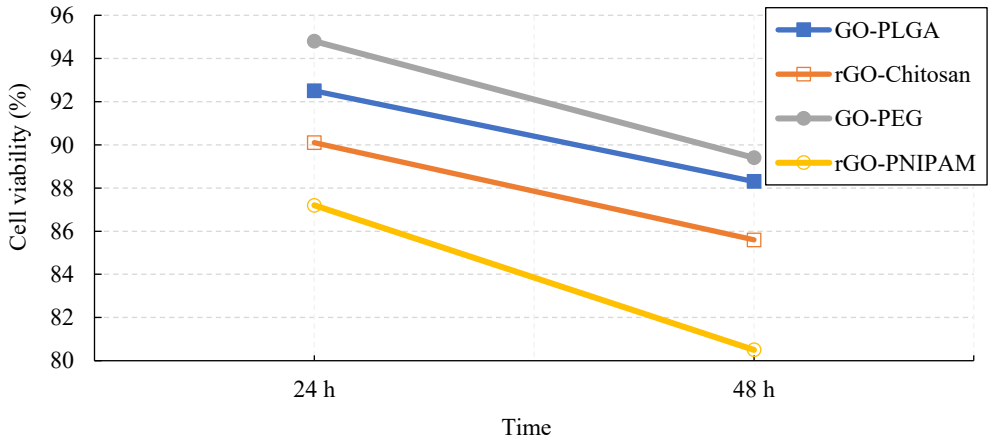

Figure 6. Graphical view of biocompatibility assessment of graphene-polymer nanocomposites.

exposure instances, it stays within ideal limits (As Indicated inside Table 6). those outcomes advise that polymer functionalization appreciably reduces graphene's cytotoxicity, making GPNCs safe for drug transport applications.

The sensible applications of GPNCs increase beyond traditional drug transport. latest research has explored their ability in gene remedy, wherein graphene-primarily based nanocarriers facilitate the shipping

of small interfering RNA (siRNA) and plasmid DNA. The robust interaction between graphene and nucleic acids guarantees solid loading, even as polymer coatings enhance cell uptake and endosomal get away. Antibiotic-loaded GPNCs have shown promising results in combating bacterial infections, with research reporting better antibacterial efficacy in comparison to standard antibiotic formulations (As proven within Figure 6). The ability of graphene to set off bacterial membrane disruption, combined with controlled antibiotic launch, makes GPNCs a powerful tool in addressing antimicrobial resistance.

CONCLUSION

Graphene-polymer nanocomposites represent a possible class of materials for complex drug delivery uses. When combined with polymers' flexibility, graphene's unique features—such as large surface area, mechanical resilience, and tunable surface chemistry—have several advantages for drug carrier design. Because of their high drug loading capacity, controlled release mechanisms, and possibility for targeted drug administration, these nanocomposites provide great opportunities for tailored and efficient therapeutic treatments. Notwithstanding these advantages, important challenges still remain regulatory approval, toxicity, biocompatibility, and scalability before these nanocomposites may be employed widely in clinical environments. The continuous research in this field, with particular focus on enhancing the safety profile, maximizing drug release kinetics, and developing efficient production techniques, will help graphene-based drug delivery systems to successfully move from the lab to practical applications. As research develops, graphene-polymer nanocomposites should become increasingly important in changing drug delivery techniques and offering creative treatment options for a variety of ailments, including infectious diseases, cancer, and neurological problems.

REFERENCES

1. Du, J.; Cheng, H.M. The fabrication, properties, and uses of graphene/polymer composites. Macromol. Chem. Phys. 2012, 213, 1060–1077.
2. Li, X.; Wang, C.; Cao, Y.; Wang, G. Functional MXene materials: Progress of their applications. Asian J. Chem. 2018, 13, 2742–2757.
3. Ha, H.W.; Choudhury, A.; Kamal, T.; Kim, D.-H.; Park, S.-Y. Effect of Chemical Modification of Graphene on Mechanical, Electrical, and Thermal Properties of Polyimide/Graphene Nanocomposites. ACS Appl. Mater. Interfaces 2012, 4, 4623–4630.
4. Niu, L.; Coleman, J.N.; Zhang, H.; Shin, H.; Chhowalla, M.; Zheng, Z. Production of Two-Dimensional Nanomaterials via Liquid-Based Direct Exfoliation. Small 2016, 12, 272–293.
5. Muktikanta Panigrahi, Munesh Chandra Adhikary. (2015). Surfactant Assisted Hydrothermal Synthesis of TiO2 Nano-spindle and their Characterizations. Advance Physics Letter, 2(2), 12-15
6. Nilesh Kumar Rajwade, Krishan Pal, Don Banjara, Rupendra Kumar Sonkar, Y. Rajesh . (2015). Study of a4-Stroke S.I. Engine Performance Using Gasoline & Hydrogen Fuel. Advance Physics Letter, 2(2), 16-21
7. Phiri, J.; Gane, P.; Maloney, T.C. General overview of graphene: Production, properties and application in polymer composites. J. Mater. Sci. Eng. B 2017, 215, 9–28.
8. D.R. Cooper, B. D'Anjou, N. Ghattamaneni, B. Harack, M. Hilke, A. Horth, et al. ISRN Condensed Matter Physics, 2012 (2012)
9. D.G. Papageorgiou, I.A. Kinloch, R.J. Young Prog Mater Sci, 90 (2017), pp. 75-127, 10.1016/j.pmatsci.2017.07.004
10. Gudarzi, M.M.; Sharif, F. Enhancement of dispersion and bonding of graphene-polymer through wet transfer of functionalized graphene oxide. Express Polym. Lett. 2012, 6, 1017–1031.
11. Goda, E.S.; Singu, B.S.; Hong, S.E.; Yoon, K.R. Good dispersion of poly(δ-gluconolactone)-grafted graphene in poly(vinyl alcohol) for significantly enhanced mechanical strength. Mater. Chem. Phys. 2020, 254, 123465.
12. Y. Yang, R. Liu, J. Wu, X. Jiang, P. Cao, X. Hu, et al. Sci Rep, 5 (2015), p. 13480, 10.1038/srep13480
13. S.K. Tiwari, R.K. Mishra, S.K. Ha, A. Huczko ChemNanoMat, 4 (2018), pp. 598-620, 10.1002/cnma.201800089

14. Bian, J.; Lin, H.L.; He, F.X.; Wei, X.W.; Chang, I.-T.; Sancaktar, E. Fabrication of microwave exfoliated graphite oxide reinforced thermoplastic polyurethane nanocomposites: Effects of filler on morphology, mechanical, thermal and conductive properties. Compos. Part A Appl. Sci. Manuf. 2013, 47, 72–82.
15. Vahedi, F.; Shahverdi, H.; Shokrieh, M.; Esmkhani, M. Effects of carbon nanotube content on the mechanical and electrical properties of epoxy-based composites. New Carbon Mater. 2014, 29, 419–425.
16. Zaccardi, F.; Santonicola, M.G.; Laurenzi, S. Quantitative assessment of nanofiller dispersion based on grayscale image analysis: A case study on epoxy/carbon nanocomposites. Compos. A Appl. Sci. Manuf. 2018, 115, 302–310.
17. Fim, F.d.C.; Basso, N.R.S.; Graebin, A.P.; Azambuja, D.S.; Galland, G.B. Thermal, electrical, and mechanical properties of polyethylene–graphene nanocomposites obtained by in situ polymerization. J. Appl. Polym. Sci. 2013, 128, 2630–2637.
18. Song, H.D.; Im, Y.-K.; Baek, J.-B.; Jeon, I.-Y. Heptene-functionalized graphitic nanoplatelets for high-performance composites of linear low-density polyethylene. Compos. Sci. Technol. 2020, 199, 108380.
19. Kang, Y.A.; Kim, M.H.; Noh, H.-J.; Baek, J.-B.; Jeon, I.-Y. Reinforcement of polystyrene using edge-styrene graphitic nanoplatelets. J. Mater. Res. Technol. 2021, 10, 662–670.
20. Tu, S.; Jiang, Q.; Zhang, X.; Alshareef, H.N. Large dielectric constant enhancement in MXene percolative polymer composites. ACS Nano 2018, 12, 3369–3377.
21. Palaniappan, M., Palanisamy, S., Khan, R. et al. Synthesis and suitability characterization of microcrystalline cellulose from Citrus x sinensis sweet orange peel fruit waste-based biomass for polymer composite applications. J Polym Res 31, 105 (2024). https://doi.org/10.1007/s10965-024-03946-0
22. Palanisamy, S., Mayandi, K., Palaniappan, M., Alavudeen, A., Rajini, N., Vannucchi de Camargo, F., & Santulli, C. (2021). Mechanical Properties of Phormium Tenax Reinforced Natural Rubber Composites. Fibers.
23. Karuppiah, G.; Kuttalam, K.C.; Palaniappan, M.; Santulli, C.; Palanisamy, S. Multiobjective Optimization of Fabrication Parameters of Jute Fiber/Polyester Composites with Egg Shell Powder and Nanoclay Filler. Molecules 2020, 25, 5579.
24. Palanisamy, S.; Kalimuthu, M.; Santulli, C.; Palaniappan, M.; Nagarajan, R.; Fragassa, C. Tailoring Epoxy Composites with Acacia caesia Bark Fibers: Evaluating the Effects of Fiber Amount and Length on Material Characteristics. Fibers 2023, 11, 63.
25. Palanisamy, Sivasubramanian, Tabrej Khan, Omar Shabbir, Shien Ming and Wu. "Mechanical, morphological and wear resistance of natural fiber / glass fiber-based polymer composites." BioResources (2024): n. pag.

