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Functionalization of natural banana trunk fiber with graphene oxide (GO) using the dip-coating method for sustainable biomedical suture application

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ABSTRACT

Developing sustainable and biocompatible sutures is crucial to overcoming the limitations of synthetic alternatives, such as non-biodegradability and adverse biological responses. This study investigates banana trunk fiber, an agricultural byproduct, as a biodegradable suture material enhanced with graphene oxide (GO) via a dip-coating technique. Extracted fibers were alkali-treated and coated with varying GO concentrations (0.25–1.00% w/v) to improve mechanical properties, stability, and antibacterial efficacy. Results indicated that sutures coated with 0.75% GO exhibited the highest tensile strength and structural integrity while maintaining an optimal swelling ratio. Results indicated that sutures coated with 0.75% GO exhibited the highest tensile strength of 850.109±1.2 MPa, demonstrating superior mechanical performance to uncoated fibers (378.614±1.1 MPa). The optimized GO coating maintained an ideal swelling ratio, and FTIR confirmed successful GO integration, while TGA demonstrated enhanced thermal stability, making the material suitable for biomedical applications. The MTT assay using human skin fibroblast cells showed 90.23±1.1% cell viability, confirming the biocompatibility and the potential to support wound closure. This research highlights the possibility of combining natural fibers with nanomaterials to create cost-effective, eco-friendly sutures with enhanced performance. Future studies should focus on large-scale manufacturing, in vivo biocompatibility assessments, and clinical trials to ensure successful translation into medical applications. By leveraging agricultural waste and advanced nanotechnology, this study presents a promising step toward sustainable medical innovations, addressing both environmental concerns and biomedical needs.

Keywords: *Biomedical, Suture, Banana trunk, Graphene oxide, Natural fiber*

1. INTRODUCTION

The primary purpose of sutures in medical applications is to help with wound closure for proper healing and prevent infection and excessive scarring [1]. Suture materials are classified into natural and synthetic polymers, with both categories encompassing absorbable and non-absorbable sutures [2]. The selection of medical sutures varies based on the specific requirements of different wound types, as the choice of suture material is predominantly dictated by the tissue being healed [3-5]. Understanding the core categories of suture materials is crucial, as they address the many surgical techniques and the distinct properties of the associated tissues [1,5].

Natural banana trunk fiber (BTF), derived from the pseudostems of banana plants, is emerging as a potential alternative to conventional surgical sutures due to its biodegradability properties, affordability, and environmental sustainability, rendering it an attractive choice amidst the increasing demand for sustainable medicinal materials [6-7]. Banana pseudostem fibers are lignocellulosic and rich in cellulose, and research indicates that the tensile strength of banana fiber sutures is analogous to commercial sutures [8-9]. However, its application is limited by its inherently high moisture absorption, inconsistent surface morphology, and lack of antibacterial properties. These drawbacks significantly affect its structural integrity, dimensional stability, and long-term usability in physiological environments [6,10]. The hydrophilic nature of the cellulose-rich BTF leads to excessive water uptake, which further compromises its mechanical properties and encourages microbial growth [11]. In addition, its unmodified fiber surface lacks the necessary functional groups to support strong interfacial interactions or bioactivity, which is critical for tissue integration and healing [12].

Doping banana trunk fiber with graphene oxide (GO) is a promising strategy to improve its physical characteristics. GO has excellent mechanical strength, oxygen-containing functional groups, and antibacterial activity, enhancing the fiber's durability, water resistance, and biocompatibility [13]. Its unique two-dimensional structure of carbon atoms

is organized in a hexagonal lattice with different oxygen-containing functional groups attached. This shape improves hydrophilicity and allows for simple dispersion in water and polar solvents, making it appropriate for various applications in nanotechnology and biomedicine [13-15]. This modification is particularly beneficial for developing sustainable, high-performance biomedical sutures, offering improved load-bearing capacity, microbial resistance, and prolonged stability in biological conditions [15-16].

Therefore, the functionalization of natural banana trunk fiber (BTF) with graphene oxide (GO) via the dip-coating method presents a compelling avenue for addressing the current limitations of BTF-based sutures. By integrating GO's exceptional physicochemical properties with the inherent biodegradability and sustainability of BTF, this study aims to develop an eco-friendly and high-performance suture material suitable for biomedical applications. This paper explores the effectiveness of the dip-coating technique in enhancing the mechanical strength, hydrophobicity, and biocompatibility functionality of BTF, ultimately contributing to the advancement of sustainable alternatives in suture technology.

2. DESIGN METHODOLOGY

2.1. Preparation of Braided Natural Banana Trunk Fiber (BTF) via Alkaline Treatment

The banana trunks were collected from Merlimau Pasir, Melaka, where the skin was manually peeled down to the inner core and processed with rollers to separate the fibers by removing excess water in the fiber trunk (see Figure 1). Then, the banana trunk fibers (BTFs) were cleaned using hot water to remove impurities and dried at a solar drying temperature. The cleaned BNFs were subjected to alkaline treatment for degumming by immersing in 4% w/v sodium hydroxide (NaOH, ≥95%, Sigma Aldrich) solution for 12 hours. The degummed BNFs were dried and subjected to manual braiding, forming 0.54±0.11 mm in diameter (USP designation 2).

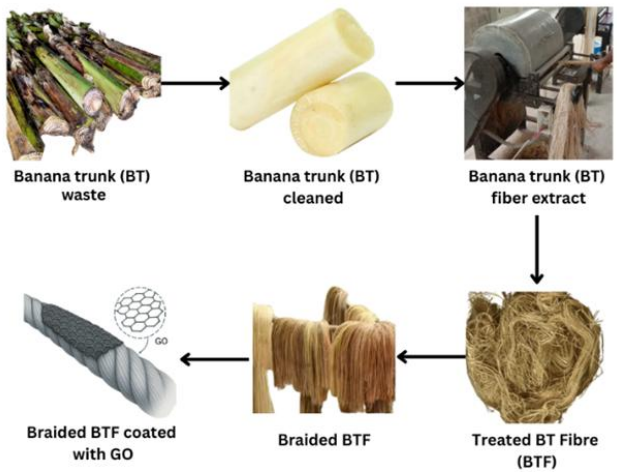

Figure 1. Overview of BTF/GO suture development

2.2. Preparation of Functionalized Braided Natural Banana Trunk Fiber (BTF) Dip-Coated with Graphene Oxide (GO)

Graphene oxide was synthesized in-house at the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia. The GO was prepared using ultrasound-assisted extraction (UAE) at 0.25%, 0.50%, 0.75%, and 1.00% w/v concentrations. Then, the BNFs were coated with GO dispersion by dip-coating for 1 hour and air-dried for 15 minutes before being subjected to a double coating process for another 1 hour. The BNFs-GO samples were dried at 50–60˚C for 3 hours and subjected to further characterization.

2.3. Fourier Transform Infrared (FTIR) Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy characterized the chemical composition and functional groups of graphene oxide-coated banana trunk fiber BTF-GO sutures. The BTF-GO sutures were dried in an oven at 50°C for 2 hours to remove residual moisture and analyzed with a wavelength range from 4000 to 500 cm^{-1}.

2.4. Tensile Testing

The tensile strength of BTF-GO sutures was evaluated using a Universal Testing Machine (UTM) following the ASTM D2256/D2256M Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method. Sutures were uniformly prepared at 5 cm lengths with a gauge length of 2 cm, tested under a 1 N load cell at a constant cross-head speed of 5 mm/min.

2.5. Degree of Swelling and Degradation Analysis

The samples were dried in a vacuum oven at 37°C for 24 hours, then weighed to determine their water uptake in Equation 1. Mass loss was measured using a balance and taken at three different temperatures: 37°C, 50°C, and 65°C. The results were presented as the mean.

$$Water\ Uptake\ (\%) = \frac{W_t - W_d}{W_d}\ x\ 100 \qquad \text{Eq. 1}$$

W_t = weight of the sample after immersion in water
W_d = initial dry weight of the sample

2.6. Cytotoxicity Analysis

To study cytotoxicity, this study uses human dermal fibroblast (HDF) cells at passages from 5th to 15th. The cells were cultured in T-flasks containing Dulbecco's Modified Eagle Medium (DMEM) supplemented with penicillin/streptomycin and fetal bovine serum. The cells are incubated at 37°C with 5% CO_2 and 95% humidity, changing the medium every 3 days. The samples were sterilized under UV light and seeded with 20 µl of cell suspension. The cells were allowed to attach for 1 hour before the medium was substituted with new culture media and incubated for 2 days. The BTF-GO sutures were evaluated for cytotoxicity according to ISO 10993-5:1999 using the MTT assay after 24 and 48 hours of incubation. The samples were compared with a control group and

treated with Trixton-X for positive control and normal culturing for negative control. Duplicates were performed, and data reported as mean ± S.D.

3. RESULTS AND DISCUSSION

3.1. FTIR Analysis on BTF Suture Surface Coating with GO

Figure 2 indicates the interaction between BTF monomers with GO after the dip coating process. The banana fiber's FTIR spectrum (Figure 2a) exhibits characteristic peaks associated with cellulose and its other components. Key peaks in a typical cellulose include a broad band around 3200–3500 cm^{-1} which is attributed to the O–H stretching vibrations from the hydroxyl groups involved in extensive hydrogen bonding within the cellulose structure. A weak peak near 2920 cm^{-1} corresponds to C–H stretching vibrations of aliphatic $-CH_2$ groups. The peak around 1730 cm^{1} indicates the presence of carbonyl (C=O) groups, which are often associated with residual hemicellulose or lignin from the BTF. The fingerprint region, especially between 1000 and 1200 cm^{-1}, displays firm peaks corresponding to C–O–C and C–O stretching vibrations of the β-1,4-glycosidic bonds in cellulose, which further increase in intensity due to interaction with GO monomers [17-18]. A peak at around 895 cm^{-1} is characteristic of the β-glycosidic linkages, confirming the cellulose backbone, which constantly appeared in Figures 2 b- 2d.

The FTIR spectra (Figure 2b-2d) of the BNT sutures coated with 0.25, 0.5, 0.75, and 1.0% w/v GO reveal notable differences in their structural properties. In the –OH stretching region (3330–3400 cm^{-1}), all samples exhibit a broad peak characteristic of heterogeneous hydrogen bonding contributed by oxygenated functional groups such as hydroxyl (–OH) and carboxyl (–COOH) in the GO [19-20]. The BTF-1.00GO sample has the broader –OH peak, suggesting a more heterogeneous hydrogen bonding environment due to incorporating higher GO presence, as indicated in Figure 2d. However, the BTF-0.75GO sample has a lower shift peak of 3330 cm^{-1} than the BTF-1.00GO sample peak of 3400 cm^{-1}, indicating stronger hydrogen bonding due to new, better interactions between GO and cellulose –OH groups. The BTF-1.00GO may have unbonded GO at the surface, leading to a higher shift peak for the –OH stretching bond.

The C–H stretching region between 2800 and 3000 cm^{-1} shows weak bands, indicating a low contribution from aliphatic–CH_2 groups in the BTF suture sample [21]. After coating with graphene oxide (GO), two distinct peaks appear at approximately 2850 cm^{-1} and 2920 cm^{-1}, corresponding to the symmetric and asymmetric stretching vibrations of $-CH_2$ [20]. These peaks become more intense and broader with increasing GO content (0.5 to 1.0 % w/v), suggesting enhanced molecular interactions and the presence of aliphatic components from GO. This change indicates that GO improves the packing and alignment of cellulose chains while contributing additional C–H signals from its structure.

The peak near 1730 cm^{-1}, corresponding to C=O stretching, becomes more prominent due to the introduction of GO's carboxyl groups. A noticeable increase in intensity around 1620–1650 cm^{-1} suggests enhanced O–H bending, likely due to hydrogen bonding between GO and cellulose [17,22-23]. Peaks in the 1200–1000 cm^{-1} region, associated with C–O–C and C–OH stretching, also intensify and broaden, reflecting overlapping vibrations from GO's oxygen-containing functional groups and the cellulose backbone. The peak near 890 cm^{-1}, attributed to β-glycosidic linkages, may show slight intensity variation, indicating some molecular-level interaction, though the cellulose structure remains intact. Overall, these changes confirm the successful incorporation of GO and the formation of strong chemical interactions at the fiber surface.

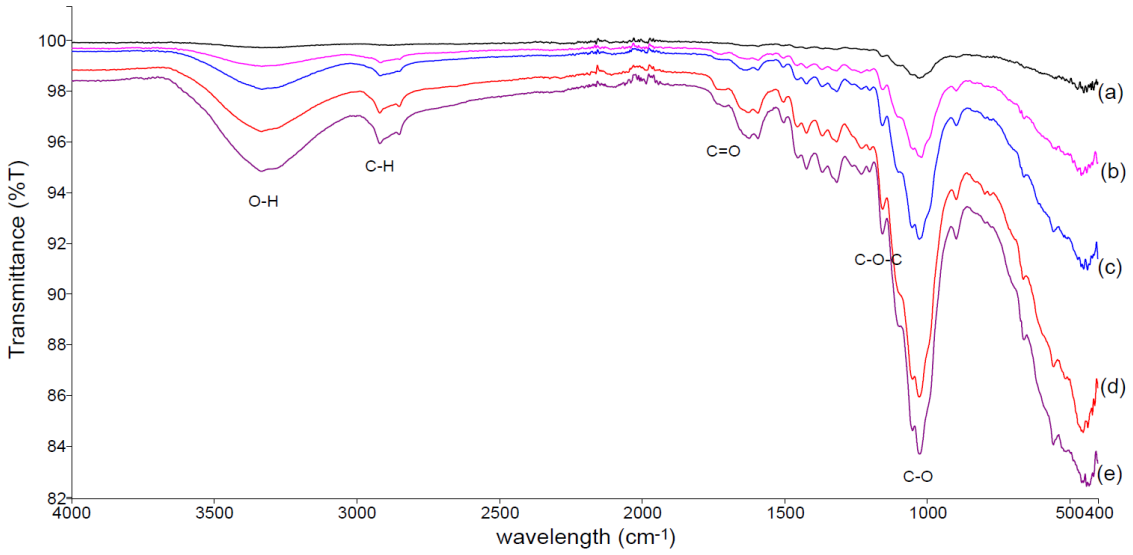

Figure 2. FTIR spectra (a) pure BTF, (b) BTF/0.25GO, (c) BTF/0.50GO, (d) BTF/0.75GO and (e) BTF/1.00GO suture samples

3.2. Tensile Strength Analysis

The tensile properties of the GO-coated banana trunk fiber (BTF) sutures showed a remarkable improvement compared to the uncoated BTF, particularly at 0.75% GO concentration, as shown in Table 1. The uncoated BTF suture displayed a UTS of 378.614 MPa, which increased to 850.109 MPa with 0.75% GO, doubling its original strength. This enhancement can be attributed to the effective surface interaction between the oxygen-containing groups (–OH, –COOH, C=O) of GO and the cellulose hydroxyl groups in BTF, leading to better load transfer and structural reinforcement as confirmed by the FTIR shifts in the –OH stretching region [24]. FTIR evidence, particularly the shift and broadening of the –OH and C=O peaks, confirms strong hydrogen bonding and polar interactions at the fiber surface, which create a robust interphase. This interfacial bonding improves adhesion, alignment, and stress transfer across the fiber–GO interface, effectively bridging cracks and resisting slippage. At the optimal 0.75% GO, these effects double the tensile strength, while higher loading (1.0%) introduces unbonded GO, slightly reducing performance. In parallel, elongation at break also increased significantly (from 4.57% to 31.27%), indicating that the GO coating improved the strength and ductility of the natural fiber suture. However, a further increase to 1.00% GO led to a drop in UTS (375.341 MPa) and elongation (2.93%), likely due to GO agglomeration and increased brittleness. This trend suggests an optimal GO loading point where mechanical reinforcement is maximized without introducing structural defects [25].

While the BTF/0.75GO suture only reached about 40% of the UTS of a commercial synthetic suture (212.42 MPa), this level of performance is scientifically valid [26]. It aligns well with findings from similar studies. For instance, Zhang et al. (2019) reported that GO-coated chitin sutures achieved tensile strengths up to 183 MPa, nearly doubling that of the pure chitin fiber [24]. Similarly, Karim et al. (2021) showed that GO-coated jute composites improved tensile strength by over 180%, with values reaching 814 MPa in specific epoxy systems [25]. Though synthetic systems inherently outperform natural ones due to their uniformity and optimized processing, the performance improvements seen in your study are promising, especially considering the sustainability and biodegradability of BTF. The combination of decent tensile properties and eco-friendliness supports the potential of GO-coated BTF sutures in biomedical applications where moderate strength is sufficient, particularly for low-tension or internal absorbable suture uses.

Table 1. Tensile properties of sutures dip-coated with different GO concentrations

Suture	UTS (MPa)	Young's modulus (GPa)	Stiffness (N/mm)	Elongation at break (%)
Pure BTF	378.614	10.914	10.089	4.570
BTF/0.25GO	591.738	27.516	12.526	10.856
BTF/0.50GO	670.918	31.702	32.590	19.811
BTF/0.75GO	850.109	48.097	71.689	31.267
BTF/1.00GO	375.341	10.953	114.797	2.931
Commercial	212.42	1.530	-	44.90

3.3. Degree of Swelling and Degradation Analysis

The swelling results in Table 2 show a clear trend of reduced water uptake with increasing GO concentration, dropping from 230.65% in pure BTF to just 46.21% in BTF/1.00GO. This does not directly imply that 1.00% GO is the optimal formulation. At higher GO loadings, particularly at 1.00%, agglomeration of GO nanosheets may occur, leading to inhomogeneous coating and microstructural defects on the fiber surface. This phenomenon often results in stress concentration points, which can negatively impact the tensile strength and flexibility of the suture material, as reported in studies by Rhazouani *et al.* (2021) [27]. These studies found that GO concentrations above 0.75% in cellulose-based or natural fiber composites can reduce mechanical integrity, despite water resistance and antibacterial behavior improvements.

Therefore, an optimal balance must be achieved, where swelling is sufficiently reduced without compromising the fiber's mechanical properties. In this context, the BTF/0.50GO or BTF/0.75GO samples likely offer the best trade-off, providing considerable water resistance (swelling reduced to 138.28% and 103.52%, respectively) while maintaining more uniform GO dispersion and better mechanical performance. This finding is consistent with previous work on GO-functionalized sutures, where 0.5–0.75% GO enhanced water resistance and tensile behavior, making it more suitable for biomedical suture applications where mechanical durability and physiological stability are equally critical.

The degradation study showed that adding GO to BTF sutures helps slow down how quickly the material breaks down. Pure BTF, without any coating, degraded the fastest, losing more than 27% of its mass at body temperature (37°C) and over 50% at higher temperatures like 65°C after 21 days. However, when GO was added, especially at higher concentrations, the sutures held up much better. For instance, the BTF with 1.00% GO only lost around 14.5% of its mass at 37 °C over the same period, showing that the GO coating provides a protective layer that resists water and enzyme attacks. This improvement happens because GO forms a thin, dense layer on the fiber surface, making it

harder for water and microbes to break the material down [22,28]. Its chemical structure and oxygen-rich groups help it stick well to the fiber and block outside elements. Using too much GO, like 1.00%, can cause problems, too. When GO particles clump together (agglomeration), they can weaken the structure and reduce the suture's flexibility and strength. So while it protects against degradation, too much GO can make the material more brittle or uneven, which isn't ideal for medical sutures.

Table 2. Swelling percentage and mass loss for BTF and BTF/GO suture samples

Suture	Swelling Percentage (%)	Mass Loss (%)					
		Temp (°C)	Day 1	Day 3	Day 7	Day 14	Day 21
Pure BTF	230.65±0.12%	37°C	3.2	6.5	12.8	20.4	27.6
		50°C	4.8	9.7	18.5	28.3	37.5
		65°C	7.5	14.2	25.9	38.6	50.1
BTF/0.25GO	161.14±0.11%	37°C	2.4	5.0	10.3	16.8	22.1
		50°C	3.6	7.8	15.4	23.9	31.4
		65°C	6.0	11.5	21.8	33.2	42.7
BTF/0.50GO	138.28±0.14%	37°C	1.9	4.1	8.6	14.2	19.0
		50°C	3.0	6.5	12.8	20.7	28.0
		65°C	5.2	10.0	18.6	28.7	39.0
BTF/0.75GO	103.52±0.11%	37°C	1.6	3.6	7.5	12.6	16.8
		50°C	2.7	5.9	11.0	18.1	24.9
		65°C	4.8	9.1	17.3	26.8	35.1
BTF/1.00GO	46.21±0.15%	37°C	1.5	3.1	6.3	10.8	14.5
		50°C	2.5	5.2	9.7	16.3	22.1
		65°C	4.4	8.3	15.5	24.6	32.0

Combining the results from the tensile strength, swelling, and degradation analyses, it becomes clear that BTF/0.75GO offers the most balanced performance among all tested samples. While higher GO loading at 1.00% significantly reduced swelling and slowed degradation, it also led to a noticeable drop in tensile strength due to GO agglomeration, which compromises the structural integrity of the suture. This concentration effectively enhances the fiber's moisture resistance and biodegradability without sacrificing flexibility and tensile durability, suggesting a synergistic improvement in overall suture performance. Therefore, further biocompatibility assessment is needed to evaluate its potential as a safe, sustainable, high-performance material for biomedical suture applications.

3.4. Cytotoxicity Analysis using MTT Assay

The cytotoxicity results clearly show in Figure 3 that including GO significantly improves the biocompatibility of banana trunk fiber (BTF) sutures. While the pure BTF suture achieved only around 57.19±1.2% cell viability, the BTF/0.75GO suture exhibited a marked increase to approximately 90.23±1.1%, indicating a much more favorable cellular response. The surface of pure BTF is porous and lacks functional groups that can prevent water molecules or microbes from penetrating the fiber structure. Exposure to moist or biological environments results in high swelling, rapid degradation, and limited mechanical strength, making it less ideal for biomedical applications like sutures [29]. The enhancement of cell viability for the BTF/0.75GO suture may be attributed to the functional groups present on GO, such as hydroxyl, carboxyl, and epoxy, which improve surface hydrophilicity and promote better cell adhesion and proliferation. Similar findings have been reported by Zhang et al. (2019), where GO-coated chitin sutures showed increased cell viability and bioactivity, and by Ka-rim *et al.* (2021), where GO-modified jute fibers enhanced mechanical and biological performance [24-25]. These results suggest that GO not only reinforces the structural integrity of natural fibers but also plays a vital role in tuning surface chemistry to support cellular health. In conclusion, including GO enhances the cytocompatibility and mechanical performance of BTF sutures. This dual improvement positions GO-coated BTF as a promising material for safe and effective biomedical suture applications.

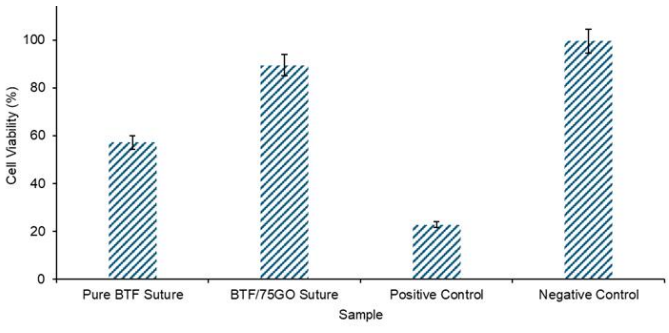

Figure 3. Cytotoxicity analysis for BTF and BTF/GO suture samples

4. CONCLUSION

This study highlights the substantial benefits of incorporating graphene oxide (GO) into banana trunk fiber (BTF) sutures, particularly at an optimal concentration of 0.75% w/v. FTIR analysis revealed clear evidence of chemical interactions between GO's oxygen-containing functional groups and the hydroxyl groups of cellulose, resulting in stronger hydrogen bonding and improved

surface functionality. These molecular-level changes translated into marked enhancements in mechanical performance, with the BTF/0.75GO sample demonstrating a significant increase in both tensile strength and elongation compared to uncoated BTF. Moreover, GO effectively reduced the swelling behavior and slowed the degradation rate of the fibers, improving their structural stability under physiological conditions. Notably, the cytotoxicity results showed that the same optimal GO concentration enhanced cell viability, indicating improved biocompatibility. When compared to findings from other natural fiber systems, such as GO-coated chitin or jute composites, these results are consistent, further validating the multifunctional role of GO in strengthening fibers while promoting cellular responses. While higher GO concentrations offer additional moisture resistance, they compromise mechanical integrity due to particle agglomeration. Therefore, the BTF/0.75GO formulation balances mechanical durability, biological safety, and functional performance, representing a promising sustainable alternative to conventional materials, offering both structural integrity and biocompatibility for future biomedical applications.

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