Effect of Carbon Fillers on Water Absorption in Polypropylene-Chitosan Composites for Fuel Cells

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Abstract

This study examines the water absorption characteristics of polypropylene-chitosan composites modified with conductive fillers to assess their potential for fuel cell applications, where both conductivity and moisture resistance are critical. Nine composite samples were prepared: a control sample (AX) containing only polypropylene and chitosan nanoparticles, and eight experimental samples divided into two groups with varying concentrations (5-20%) of either activated carbon (B1-B4) or graphene (C1-C4) as conductive fillers. Water absorption was measured over seven days to evaluate how each filler type and concentration impacted moisture uptake. Results showed that the control sample exhibited the lowest water absorption, underscoring the inherent moisture resistance of the polypropylene-chitosan matrix. However, the absence of conductive fillers in AX limits its potential for fuel cell applications. Among the activated carbon-enhanced samples, Sample B2 (10% activated carbon) demonstrated the most favorable balance of moderate water absorption and potential conductivity. In the graphene group, Sample C2 (10% graphene) displayed a similar balance, with stable moisture resistance and likely enhanced electrical conductivity due to graphene's properties. Higher filler concentrations in both groups increased water absorption, suggesting that excessive filler can introduce porosity, thereby reducing material stability. The findings indicate that composites containing 10% conductive filler—either activated carbon or graphene—are optimal, combining moisture resistance with expected conductivity. These materials show promise for further testing in fuel cell environments, where their properties could support both durability and performance.

Keywords: Plastic wastes (PP), Activated carbon, Graphene, Water Absorption, Waste-to-energy, Fuel cells, Polypropylene-Chitosan Composite.

1.0   Introduction

The development of advanced materials for energy applications, particularly fuel cells, has gained significant attention due to the global demand for clean, efficient, and sustainable energy sources. Fuel cells, which generate electricity through electrochemical reactions, rely on materials that combine conductivity with structural durability under varying environmental conditions, including high humidity (Adelaja, 2015). A key challenge in designing these materials lies in achieving a balance between hydrophobicity to prevent excessive moisture absorption and conductivity to enable efficient electron transport (Udorah *et al.* , 2023; Park *et al.* , 2019). Moisture absorption is particularly important in fuel cell applications, as it can lead to swelling, structural weakening, and compromised performance over time (Stepashkina *et al.* , 2014; Zhao *et al.* , 2020). This study focuses on the water absorption behavior of polypropylene-chitosan composites modified with conductive fillers to assess their suitability for fuel cell applications.

Polypropylene, a thermoplastic polymer known for its chemical resistance and mechanical strength, is an appealing matrix for composite materials in fuel cell applications due to its natural hydrophobicity (Gupta *et al.* , 2018). However, the addition of chitosan, a biocompatible and biodegradable polysaccharide, can enhance the composite's stability and potentially improve its interaction with conductive fillers (Nguyen *et al.* , 2021). Chitosan is also known for its moderate hydrophilicity, which, while generally advantageous for material compatibility, can increase water uptake. To counterbalance this property, conductive fillers such as activated carbon and graphene have been investigated for their ability to enhance the composite's conductivity while minimally impacting its water absorption profile (Yong *et al.* , 2022).

Conductive fillers play a crucial role in optimizing composite materials for fuel cells. Activated carbon, known for its high surface area and relatively low cost, is widely used as a conductive filler in various applications. Its incorporation into polymer matrices has been shown to improve electrical conductivity and thermal stability (Isil *et al.* , 2016; Geethapriya and Barathan, 2016); however, activated carbon's inherently porous structure can lead to increased water absorption in composite materials (Surya and Michael, 2021; Schweitzer *et al.*, 2019). Graphene, a single-layer carbon allotrope, offers an alternative due to its exceptional conductivity and mechanical strength (Balandin *et al.* , 2011). The incorporation of graphene into polymer composites has been shown to significantly enhance their conductivity and thermal properties, and graphene's two-dimensional structure offers a less porous pathway compared to activated carbon, potentially reducing moisture absorption (Bolotin *et al.* , 2008).

This study evaluates the effects of varying concentrations (5-20%) of activated carbon and graphene fillers on the water absorption characteristics of polypropylene-chitosan composites. Nine samples were prepared, with a control sample (AX) containing only polypropylene and chitosan nanoparticles, and two groups with activated carbon (B1-B4) or graphene (C1-C4) as conductive fillers. Water absorption measurements were taken over a seven-day period to assess how each filler type and concentration impacted the composite's ability to resist moisture ingress. The goal is to identify the filler concentration that provides an optimal balance of conductivity and moisture resistance, key criteria for potential use in fuel cells.

By comparing the water absorption profiles of these composites, this research aims to contribute valuable insights into the material properties required for high-performance fuel cell components. While prior studies have demonstrated the benefits of conductive fillers in polymer matrices (Adelaja *et al.* , 2024; Gupta *et al.* , 2018; Schweitzer *et al.* , 2019); limited research has focused specifically on optimizing filler concentrations for applications in fuel cells under humid conditions. Findings from this study are expected to provide a foundation for further research on durable, conductive, and moisture-resistant composites, ultimately advancing the development of more robust materials for clean energy applications.

2.0 Materials and Method

2.1 Experimental materials

In this study, commercially available plastic waste, specifically a derivative of polypropylene, was utilized. The research focused on selecting commodity polymers that are widely available and exhibit excellent applicability in fuel cell environments. Chitosan nanoparticles, derived from chitin, were incorporated as fillers in conjunction with the polypropylene matrix to create electrically conductive biocomposites. The selection of these fillers was based on their ability to enhance the conductivity of the composites while ensuring effective biodegradability, low cost, and high availability.

2.2 Sourcing and Collection of Materials

The polypropylene waste used in this research was sourced from the Federal University of Technology, Akure (FUTA) community. The material was thoroughly washed and subsequently shredded into pellets of sizes 1.69 mm and 3.21 mm at ZL Alliance Global, Alagbaka Akure, Nigeria. Additionally, banana pseudo-stem waste was collected from a banana farm located at the FUTA South gate in Akure, Nigeria. Chitosan was procured from a seafood company in Lagos, Nigeria, with an average particle size of 80 mm and a degree of deacetylation (DD) of 81%.

2.3 Sample Preparation

2.3.1 Preparation of Nano chitosan

Nano chitosan (CNP) was prepared using a modified method based on Daramola and Adelaja (2020). A total of 30 g of chitosan powder was dissolved in 2 liters of 2% acetic acid. The solution was stirred for 24 hours at a temperature of 60°C, followed by the addition of 73.4g of Sodium tripolyphosphate (TPP) to facilitate the formation of nanoparticles. The resultant sample (Chitosan Nanoparticle CNP) was then filtered and washed severally with distilled water which was made to stand for a day before been filtered with a sintered glass. Obtained samples were then oven dried for 48hrs and grinded to powder.

2.3.2 Polypropylene Composite Blend Formulation

The blend formulation for the preparation of PP/CNP composite was done by varying the percentage weight of PP and CNP in ratio 100:0, 90:10 80:20 70:30 60:40 to obtain an optimal sample where PP/unfilled (100:0) was used as the CONTROL 1, as presented in table 2.1.

Table 2.1: Blend formulation for PP/CNP, PP/CNP/AC and PP/CNP/Gr composite sample

Designation	Sample	Designation	Sample	Designation	Sample
A0	PP	X	PP/CNPopt	X	PP/CNPopt
A1	PP/CNP10%	B1	X/AC5%	C1	X/Gr5%
A2	PP/CNP20%	B2	X/AC10%	C2	X/Gr10%
A3	PP/CNP30%	B3	X/AC15%	C3	X/Gr15%
A4	PP/CNP40%	B4	X/AC20%	C4	X/Gr20%

The optimized sample of PP/CNP was labeled X, which serve as CONTROL 2, a constant used for X/AC and X/Gr bio composite blend. X/AC and X/Gr bio composites were prepared by blending the optimized sample (X) obtained above with 5%, 10%, 15% and 20% of each of the conductive fillers (Gr and AC).

For the blending, solvent casting method as carried out by Siemann (2005) was employed. Polypropylene (PP) was dissolved in 0.067g/ml Xylene at 164oC using a magnetic stirrer hot plate. Fillers (CNP, AC and Gr) were added to the dissolved PP. It was allowed to cool down and was poured into a mold. The resulted blend; bio composite was sundried to drain the organic solvent left in the sample. This method was carried out for the entire formulations as shown in Table 3.1. The optimized sample was then selected after being subjected to analytical tests.

2.4 Water Absorption Characterization of the Synthesized Composites

The water absorption test is a critical evaluation method used to assess the moisture uptake characteristics and the capacity of polypropylene-chitosan nanoparticle (PP-CNP) composites. This test is crucial for understanding the material's behavior in various environmental conditions, particularly in applications where moisture exposure is a factor. The water absorption test involved measuring the weight of each composite sample at regular intervals over a period of seven days, according to the modified method of Raheem (2019). The initial weight of each sample was recorded on Day 0, followed by daily measurements to track changes in weight due to water absorption. The results were documented in grams, and the weight increase was analyzed to determine the water absorption characteristics of each sample. The samples were removed 24hourly for seven days and weight gain of the samples were measured at different time intervals using equation 3.1.

$$Increase\ in\ weight\ (\%) = \frac{Wet\ Weight - Condition\ Weight}{Condition\ Weight} \times 100 \qquad [1]$$

3.0 Results and Discussion

3.1 Optimization of the Polypropylene-Chitosan Composites

Fuel cells benefit from materials that balance conductivity and moisture resistance, as excessive water uptake could lead to mechanical degradation and reduced efficiency over time. The water absorption test measures the amount of water absorbed by the samples over time. In this case, Table 3.1 shows the result of the five composite samples (A0, A1, A2, A3, and A4) and their respective weights in grams on each day of the test. The water absorption test results provide valuable insights into the behavior of the samples regarding their ability to absorb water.

Table 3.1: Water absorption result of the PP-CNP composite

Sample	Weight loss (g)							
	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
A0	3g	3.01	3.02	3.03	3.04	3.04	3.05	3.05
A1	3g	3.03	3.06	3.07	3.09	3.1	3.11	3.11
A2	3g	3.03	3.05	3.09	3.1	3.1	3.11	3.11
A3	3g	3.03	3.03	3.05	3.06	3.07	3.07	3.07
A4	3g	3.04	3.07	3.09	3.1	3.11	3.11	3.11

The data indicate that all samples exhibited an increase in weight over the testing period, signifying water absorption. Notably, the rate of water absorption varied among the different composite formulations. Sample A1, which contained 10% chitosan nanoparticles, demonstrated the highest water absorption capacity, with a consistent increase in weight observed throughout the test. The weight gain observed in Sample A1 indicates that the chitosan nanoparticles facilitate water penetration into the polypropylene matrix, thereby creating additional pathways for moisture to be absorbed. This behavior can be attributed to the hydrophilic properties of chitosan, which enhance the composite's ability to absorb moisture (Weng *et al.* , 2012).

In contrast, the neat polypropylene sample (A0) displayed a relatively low water absorption rate, consistent with its hydrophobic nature. The gradual increase in weight for A0 suggests a uniform structure that allows for limited water penetration. The observed variations in water absorption rates among the samples can be linked to several factors, including the composition of the materials, structural characteristics, porosity, and surface properties (Udorah *et al.* , 2023). The results for Sample A0 serve as a baseline for evaluating the impact of chitosan nanoparticles on water absorption. Samples A2, A3 and A4, which contain even higher percentages of chitosan nanoparticles, also exhibited increased water absorption capabilities. However, the rate of weight increase varied among these samples, suggesting that factors such as the size, distribution, and morphology of the chitosan nanoparticles may play a critical role in determining the water absorption characteristics of the composites (Chen *et al.* , 2019).. The porous structure of chitosan nanoparticles is likely a contributing factor to the enhanced water retention capabilities observed in these samples. The presence of pores within the chitosan matrix allows for greater water

penetration and retention, leading to a more significant increase in weight over time (Gopi *et al.* , 2017).

The incorporation of chitosan nanoparticles not only improved the water absorption capacity but also indicated potential modifications in the composite's microstructure, which may enhance its performance in applications requiring moisture resistance.

3.2 Effects of the carbon fillers on the synthesized Polypropylene-Chitosan composites

Fuel cells rely on materials that can offer not only high conductivity but also resistance to excessive moisture absorption, as prolonged water exposure can lead to material degradation and instability. In this study, nine different composite samples were further analyzed to evaluate their water absorption behavior, comparing how varying concentrations of conductive fillers (activated carbon and graphene) influence moisture uptake in a polypropylene and chitosan nanoparticle matrix, and the result is presented in Table 3.2.

Table 3.2: Water absorption result of the PP-CNP composite

Sample	Weight loss (g)							
	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
AX	3g	3.03	3.03	3.05	3.06	3.07	3.07	3.07
B1	3g	3.02g	3.07g	3.08g	3.13g	3.16g	3.18g	3.19g
B2	3g	3.04g	3.06g	3.09g	3.12g	3.15g	3.16g	3.16g
B3	3g	3.06g	3.21g	3.22g	3.24g	3.25g	3.26g	3.26g
B4	3g	3.04g	3.13g	3.14g	3.19g	3.21g	3.22g	3.22g
C1	3g	3.07g	3.22g	3.25g	3.26g	3.28g	3.28g	3.28g
C2	3g	3.05g	3.1g	3.11g	3.12g	3.12g	3.13g	3.13g
C3	3g	3.09g	3.19g	3.23g	3.26g	3.29g	3.31g	3.32g
C4	3g	3.15g	3.27g	3.27g	3.37g	3.41g	3.43g	3.44g

Sample AX served as a control containing only polypropylene and chitosan nanoparticles (the optimized sample) , while the other samples incorporated different levels of activated carbon (B1 to B4) or graphene (C1 to C4) as conductive fillers. Understanding the effects of these fillers on water absorption is crucial for optimizing materials for fuel cells, where both conductivity and durability under humid conditions are essential.

The control sample, AX, which contained only polypropylene and chitosan nanoparticles (the optimized sample), exhibited the lowest water absorption, increasing from an initial weight of 3g to 3.07g by Day 7. Polypropylene is known for its hydrophobic characteristics, which generally prevent moisture absorption, while chitosan, a biopolymer with moderate hydrophilicity, is widely

recognized for its biocompatibility and mechanical stability (Yong *et al.*, 2022). The limited water uptake observed in Sample AX suggests that the polypropylene-chitosan matrix itself provides a strong baseline for moisture resistance, likely due to the low porosity and good distribution of chitosan within the polypropylene. This characteristic establishes Sample AX as a control benchmark against which the effects of conductive fillers on water absorption can be measured.

Activated carbon was added to samples B1 through B4 in increasing percentages, ranging from 5% in B1 to 20% in B4. Sample B1, with 5% activated carbon, demonstrated a gradual increase in water absorption from 3.02g on Day 1 to 3.19g by Day 7. The presence of activated carbon, which has a high surface area and is known to have hygroscopic properties, may lead to increased water absorption, although the effect here remains modest (Adelaja *et al.*, 2024; Zhao *et al.*, 2020). This relatively low water uptake at 5% carbon content indicates that B1 could maintain a balance between providing moderate conductivity and preserving structural integrity under humid conditions. Sample B2, with 10% activated carbon, exhibited slightly higher water absorption, ending at 3.27g by Day 7. This increase, while modest, suggests that the additional activated carbon slightly increases the composite's porosity, which can facilitate water uptake. However, the water absorption in B2 remains stable, suggesting that it can retain structural integrity, which is critical for applications requiring consistent performance in moisture-exposed environments, such as fuel cells (Schweitzer *et al.*, 2019).

As the activated carbon content increased in samples B3 (15%) and B4 (20%), water absorption also rose, reaching 3.26g and 3.37g on Day 7, respectively. This trend indicates that higher concentrations of activated carbon introduce more pathways for moisture ingress, likely due to the inherent porosity and large surface area of activated carbon particles, which can hold water within their structure (Zhao *et al.*, 2020). For fuel cell applications, excessive water absorption could weaken the material's structure, leading to swelling or degradation over time (Udorah *et al.*, 2023). Thus, while B3 and B4 likely offer improved conductivity compared to B1 and B2, their increased water absorption suggests a trade-off that may make them less suitable for applications where dimensional stability is essential under humid conditions. Overall, Sample B2, containing 10% activated carbon, represents the most promising option within this subgroup, as it provides a balanced profile of conductivity and controlled moisture uptake.

Samples C1 to C4 incorporated graphene as a conductive filler at concentrations of 5%, 10%, 15%, and 20%, respectively. Graphene is celebrated for its exceptional electrical conductivity and strength, though its interaction with water can vary depending on dispersion within the composite. Sample C1, with 5% graphene, showed a stable and moderate increase in water absorption from 3.07g on Day 1 to 3.28g by Day 7. This modest absorption suggests that the low graphene content is well-dispersed within the matrix, preventing significant moisture ingress. The stability observed here points to C1 as a potentially effective material for fuel cells, where controlled water absorption and enhanced conductivity are both essential. Sample C2, containing 10% graphene, displayed a similar trend, with water absorption reaching 3.29g by Day 7. The minimal difference between C1 and C2 suggests that up to 10% graphene can be introduced without substantially increasing water absorption, while still enhancing conductivity due to graphene's high electron mobility (Bolotin *et al.*, 2008).

At higher graphene concentrations, however, water absorption became more pronounced. Sample C3, containing 15% graphene, ended at 3.32g on Day 7, while Sample C4, with 20% graphene, absorbed the most water in this group, reaching 3.44g. This trend likely reflects challenges associated with dispersing larger quantities of graphene within the polypropylene-chitosan matrix. When high concentrations of graphene are present, there is a greater likelihood of agglomeration, where graphene particles cluster together, creating pathways for water ingress through micro-channels (Balandin *et al. ,* 2011). For fuel cell applications, such increased water absorption can negatively affect material stability, potentially leading to compromised mechanical and conductive performance over time. Therefore, similar to the activated carbon group, it appears that a lower filler concentration—specifically, 10% in the case of Sample C2—provides the best balance of enhanced conductivity and moisture resistance.

4.0   Conclusion

This study investigated the water absorption behavior of polypropylene-chitosan composites modified with conductive fillers (activated carbon and graphene) to evaluate their suitability for fuel cell applications. Nine samples were tested, including a control sample (AX) with no conductive filler, and two groups of samples containing varying concentrations of activated carbon (B1-B4) and graphene (C1-C4). The results demonstrate that the addition of conductive fillers impacts water absorption differently depending on both the type and concentration of the filler. The use of moderate filler levels—specifically, 10% activated carbon (B2) or 10% grapheme (C2)—appears to provide the best compromise between enhanced conductivity and stable water absorption. These composites, B2 and C2, may thus be viable candidates for further testing in fuel cell applications, where their balance of properties could support both conductivity and durability under humid operational conditions. Future studies should consider additional performance metrics, such as electrical conductivity testing and long-term durability assessments, to confirm the suitability of these materials for practical fuel cell use.

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