

Research Article

Comparative Biodegradation Studies of Butyl and Dodecyl - Functionalized Carbon Nanofibers Dispersed in Cellulose Acetate Polymer Nanocomposites

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Abstract

Biodegradable nanocomposites incorporating carbon nanofibers (CNFs) have gained significant traction due to their environmentally friendly nature. The use of functionalized CNFs enhances the mechanical, thermal, and electrical properties of nanocomposites. The ultimate properties and biodegradation rate of these nanocomposites are significantly influenced by the type and structure of the CNFs dispersed within the biodegradable polymer matrix. Nanocomposites were prepared by blending 0.2% w/w of the functionalized butyl, and dodecyl CNFs in cellulose acetate polymer matrix. The study sought to establish the effect of the butyl, and dodecyl moieties on the degradation rate of biodegradable cellulose acetate. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were used to determine the dispersion of CNFs within the polymer matrix and the surface characteristics of the resulting nanocomposites. Respirometry (CO₂ emission) and gravimetry (change in mass) techniques were used to determine the biodegradation rate of the nanocomposites. The study found out that incorporation of functionalized CNFs into the biodegradable polymer matrix had an impact on the biodegradation rates of the formed nanocomposites. From the cumulative amounts of CO₂ evolved during the respirometry and cumulative weight lost during the test period, the nanocomposites had a reduced rate of degradation compared to the reference blank. This could be attributed to an increase in polymer crystallinity caused by the addition of the alkyl moieties that increased the adherence of the CNFs to the polymer matrix. Individual alkyl functionalized nanocomposite also had different rates of degradation with the butyl nanocomposite degrading much faster than the dodecyl, respectively. Overall, the results indicated a slight increase in the time required for the nanocomposite to degrade to less than 1% of the original sample as compared to the reference blank. The study and its findings have generated new scientific knowledge that could be relevant in the fabrication biodegradable nanocomposites based on a diverse range of other polymeric and nonpolymeric matrices and importantly approximately how long the fibers can be in the environment after their useful life.

Keywords

Carbon Nanofibers, Nanocomposites, Biodegradation

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1. Introduction

Polymer nanocomposites consist of a polymer or resin and an organic or inorganic filler that is uniformly distributed in the matrix [1]. In cases where the polymer or filler is biodegradable, the nanocomposite generated is referred to as a bio-nanocomposite meaning that it will undergo degradation when exposed to the environment for long periods [2]. Nanocomposites derived from poly (lactic acid), cellulose Acetate, and polyhydroxyalkanoates are all considered to be biodegradable [3].

The biodegradable polymer nanocomposites have generated a lot of research interest in recent years due to the depletion of the fossil reserves that have been a major resource of synthetic or non-biodegradable polymers and because they are more environmentally friendly than plastics or non-biodegradable polymers [2]. Their elimination from the environment can be achieved through a variety of methods, but biodegradation and bio-recycling are more impactful. Biodegradable polymers have emerged as a plausible alternative to non-biodegradable polymers in addressing the polymer waste management as they do not last very long in the environment after finishing their useful work life [2, 4].

Biodegradability of nanocomposites prepared from polymer/resin and/or filler to determine the rates of biodegradation have previously been studied. The earlier studies have shown that the filler on its own might not have a significant impact on the breakdown of the nanocomposite. In a study by Roy and sengupta to establish the effect of incorporating carbon nanofibers and nanotubes on the biodegradation of thermoplastic polymers [5], it was reported that besides enhancing mechanical, thermal, and electric properties, the incorporation also increased the biodegradability of the polymers under natural environmental conditions [6]. The mechanisms of nanocomposite degradation in the environment can be divided into two categories: (i) Physical mechanisms, such as flaking, cracking, and embrittlement, leading to changes in the bulk structure of the sample; or (ii) Chemical processes in which bond cleavage or oxidation of long polymer chains occurs forming molecules with significantly shorter chain lengths [7, 8]. The research reports the development of environmentally friendly materials with enhanced properties for potential applications in various fields where biodegradability and im-

proved material performance are crucial.

The main methods used in investigating the biodegradation of polymers are based on the change in the preceding gaseous phase of a closed test system which can either be aerobic or anaerobic (respirometry) [9]. The second method utilizes the changes in the mass (gravimetric) of the main sample as the nanocomposite is exposed to adverse environmental conditions. The tests have been standardized under the ASTM D5338 system that is used in assessing the anaerobic, aerobic, and biodegradation of polymers in a laboratory setup that has a similar texture and composition to the environmental conditions that the nanocomposite will be exposed to in a natural setting [9].

Polymer biodegradation involves both abiotic and biotic processes where the polymers first undergo thermal, chemical, mechanical, and photodegradation [10]. Then microbial activity on both the surface and inside of the material through enzymatic degradation and bio-fragmentation. The microbes first attach themselves to the surface of the sample, they then produce extracellular enzymes that attack and break up the cleavages in the matrix producing carbon dioxide, water, and Methane [11]. The life span of the polymer nanocomposite can be estimated by extrapolation of the time taken for the sample to biodegrade 99% of its initial mass [12]. Mainly two methods have been used, the Arrhenius extrapolation is based on the determination of a degradation activation energy that gives the relationship between temperature and the rate of degradation [13, 14]. This can be expressed as

$$k = A \exp \left(-\frac{E_a}{RT} \right) \quad (1)$$

k = the rate of degradation, A = the material constant, E_a = the activation energy, R and T are universal gas constant and absolute temperature respectively.

However, studies have shown that the conditions change as the degradation takes place and therefore the temperature cannot be constant [13]. The Arrhenius model best works in industrial degradation where temperatures are high and rate determining.

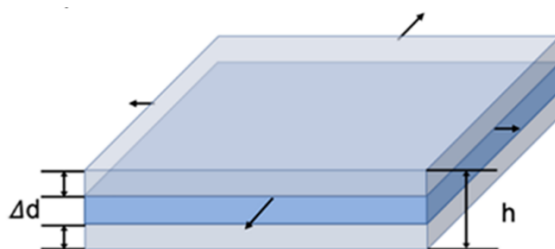


Figure 1. Section of a flat nanocomposite with a thickness of h , and a layer Δd [7].

The second method of estimating the lifespan of the sample in the environment is the specific surface degradation rate (SSDR) that extrapolates the degradation processes using the initial degradation rate RD of the sample when placed in relevant environmental circumstances [15, 16]. The method is only viable when degradation refers to the overall loss of mass from the initial nanocomposite sample and it is appropriate for large pieces of nanocomposites, however, loss of the nanoparticle fragments may reduce the initial mass without necessarily reducing the total amount of nanocomposite present [17]. Applying the method to a flat nanocomposite figure 1 that has a thickness of h , we can broadly define the SSDR as the volume of material lost by the removal of a layer of thickness Δd in a specified time [7].

The nanocomposite degradation rate R_D can then be broadly defined as the differential mass loss of a sample in unit time.

$$R_D = -\frac{dM}{dt} = kSA \quad (2)$$

S_A = the total surface area of the sample

Majorly, biodegradation takes place at the exposed surface of the nanocomposite, and therefore the rate of degradation R_D is directly proportional to the surface area A of the sample [7].

The surface degradation speed k_d can be defined using the dimensions m^{-1} , dividing the constant k by the density ρ in $kg\ m^{-3}$ of the samples/nanocomposites, equation (2) becomes [7].

$$-\frac{dM}{dt} = k_d \rho SA \quad (3)$$

If the density is also constant the above equation can be rearranged into an algebraic equation as shown below [18].

$$M_t = M_0 - k_d \rho SA t \quad (4)$$

From equation (4)

We can therefore determine the time t_d as ample will take to biodegrade [7].

$$t_d = \frac{M_0}{k_d \rho SA} = \frac{V_0}{k_d SA} \quad (5)$$

Several assumptions are made that degradation is a first-order reaction dependent on the surface area and density of the sample that will remain constant as it degrades.

In this study, we report the biodegradation of carbon nanocomposites of polymethyl methacrylate-based functionalized carbon nanofibers in cellulose acetate polymer by use of both respiratory and gravimetric analysis. We also report the estimated life span of the samples in the environment using SSDR extrapolation technique with the assumption

that the surface area A of the sample remains constant during the biodegradation.

2. Materials and Methods

All the chemicals used were of AR grade, they included I) Poly methyl methacrylate, Lithium metal, Dimethylformamide, Dichloromethane, Ethanol, Chloroform, Iodobutane, Iodododecane, and Iodoacetamide, Ammonia solution, Hexane, Cetyltrimethylammonium bromide, polyethylene glycol and 0.2 μm PTFE membrane filter, Methanol for synthesis. Hydrochloric Acid, and Potassium hydroxide.

2.1. Preparation of Carbon Nanofibers

The preparation of carbon nanofibers was carried out as previously described with slight modifications [19]. Exactly 80 mg of analytical grade polymethyl methyl acrylate (Sigma Aldrich) was dissolved in 10 ml of a dichloromethane/ dimethylformamide mixture in a ratio of 2:3 and stirred using a magnetic stirrer for 3 hrs. The polymer solution was electrospun at 18K v, 22 $^{\circ}C$, and 45% humidity (BK precision 1901 30 kV/5mA). The nanofibers were deposited on an aluminum foil placed 15 cm away from the tip of the pipette. The resulting white fibers were allowed to dry at room temperature for 12 hrs, the white nanofibers purged with dry nitrogen gas in carbonization tube to create an inert environment and heated to $\sim 400\ ^{\circ}C$ to yield the black carbon nanofibers.

2.2. Functionalization of Carbon Nanofibers

Functionalization of the carbon nanofibers was carried out as previously described with slight modifications [20, 21]. Exactly 2.0 grams (0.16 mol) of carbon nanofiber, 120 ml of 30% ammonia solution in water, 1.68 grams (0.24 mol) of metallic lithium, and 14.5 ml (0.144 mol) of alkyl iodide (butyl and dodecyl) was added to a dry 500 ml one-neck round-bottomed flask and the mixture stirred for 12 hrs with the slow evaporation of ammonia gas. The mixture was cooled in an ice bath with a slow addition of 100 ml methanol, followed by 200 ml of water distilled water. The resulting mixture was acidified with 50 ml of 10% HCl, before the addition of 250 ml of n-hexane, on shaking the functionalized carbon nanofibers were extracted into the n-hexane, filtered, and washed with ethanol. The nanofibers were oven-dried at 80 $^{\circ}C$ and used in fabricating the nanocomposites.

2.3. Fabrication of 0.2% Alkyl Nanocomposites

The nanocomposites were prepared through the solution casting technique using acetone- dimethylformamide solvent mixture in a ratio 1:1 as the solvent system [22].

The prepared films had the following functionalized CNF

compositions: 0.2 wt%, a of the functionalized nanofiber with Cetyltrimethylammonium bromide (CTAB) used as a dispersant to ensure that the functionalized nanofibers were distributed evenly in the solution matrix cast. PEG 1500 was

used as a plasticizer to enhance the flexibility of the nanocomposites and its composition was kept at a constant 20%. Sample nanocomposites that were prepared for analysis are shown in Figure 2 below.

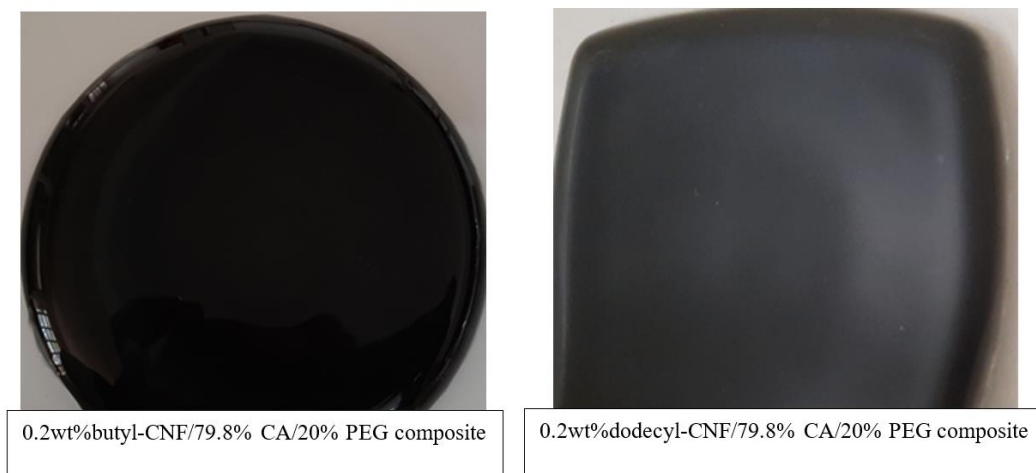


Figure 2. Sample picture of fabricated nanocomposites.

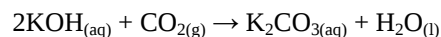
2.4. Characterization of the Nanocomposites

Characterization of resulting nanocomposites was carried out using Scanning Electron Microscopy and Energy Dispersive Spectroscopy (EDS) using a Zeiss EVO LS15 Scanning Electron Microscope, with an accelerating voltage of 5 or 8 kV. Film samples were prepared by embedding and leaving them to dry overnight. A microtome was then used to cut a cross section of the sample and resin on one side resulting in a smooth surface of the sample.

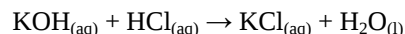
2.5. Biodegradability Test

The biodegradation test was carried out as previously described with slight modifications [23]. Approximately 200 grams of soil was sieved to a particle size of at least 2 mm and placed in a 1000 ml desiccator, exactly 8 g of compost was added and mixed thoroughly. The soil pH was adjusted to approximately 7 by addition of calcium hydroxide and moisture content adjusted to 60% by the addition of distilled water. About 500 mg of nanocomposite sample was put in the soil sample in a glass desiccator. Separately 50 ml of distilled water in a 100 ml beaker and 20 ml of 0.5M KOH in a 50 ml beaker were carefully placed inside the desiccator and the desiccator lid replaced ensuring it was airtight. The setup was allowed to stand for 14 days. After 14 days the KOH beaker was removed, and the KOH titrated against HCl.

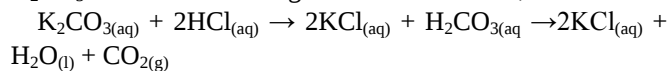
In stoichiometric analysis with KOH, the CO₂ evolved during the aerobic biodegradation of nanocomposite was absorbed by potassium hydroxide as shown in the equation below.



The unreacted KOH is then titrated with HCl as follows



To determine the amount of CO₂ from the sample, the K₂CO₃ was back titrated against HCl as follows;



From the equation above one mole of K₂CO₃ reacts with 2 moles of HCl to yield one mole of carbon dioxide, i.e. 2 moles of the acid yields one mole of CO₂ evolved from the reaction. Therefore, to determine the mass of CO₂ evolved we multiply the moles of half the moles HCl used in titration by the molar mass of CO₂ = 44.

$$\text{Mass (g) of CO}_2 = (0.5) \times \text{ml HCl} \times 44$$

The nanocomposite sample was washed thoroughly using distilled water, dried at 80 °C in the oven and its weight recorded. The procedure was then repeated with the same sample and the same soil in a desiccator but with another set of 50 ml of distilled water in a 100 ml beaker and 20 ml of 0.5M KOH in a 50 ml beaker for a period of 14 days. The experimental setup was repeated for all the 0.2% filler nanocomposites.

3. Results and Discussion

3.1. Scanning Electron Microscopy and Energy Dispersion Spectroscopy Analysis

Scanning Electron Microscopy was used to study the cross-section of the prepared CNF/CA nanocomposites to ascertain the dispersion of the fibres within the composite films. A SEM image of 0.2 wt% butyl CNF/79% CA/20%

PEG composite cross-section prepared by microtomy is shown in Figure 3. The image shows no apparent aggregation of CNFs in the cross-section and minimal visible CNF pull-outs from the CA matrix indicating good interfacial ad-

hesion between the CNF and CA matrix. The enhanced interfacial adhesion is expected to contribute toward improved mechanical properties of the CNF nanocomposite [24].

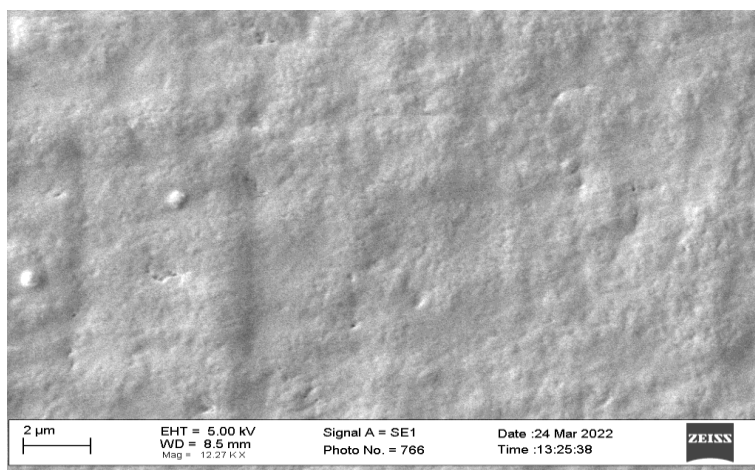


Figure 3. Scanning Electron Microscopy image of 0.2% butyl nanocomposite.

The EDS was done to determine the composition of the new composites of the butyl and dodecyl, Figure 4 is an EDS spectrum of 0.2% dodecyl nanocomposite. The EDS spectra

shows that the functionalized CNF/CA composite are mainly composed of carbon (~95.2% weight) and oxygen (~4.8% weight).

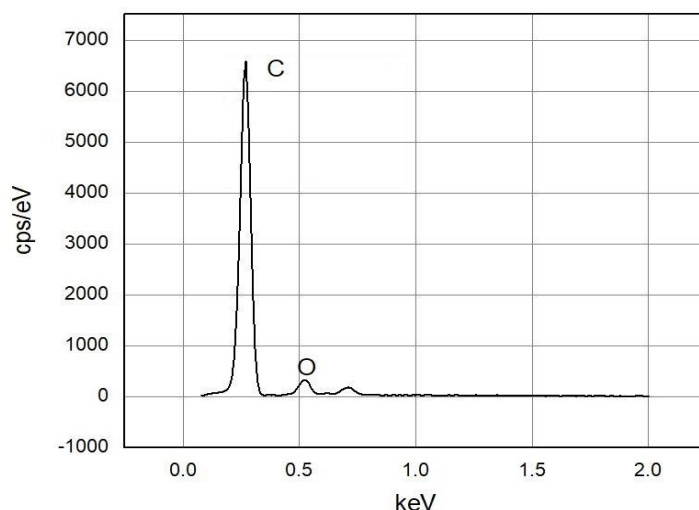


Figure 4. Electron Dispersion spectra of 0.2wt% dodecyl functionalized nanocomposite.

3.2. Biodegradation of the Nanocomposites

The respirometry biodegradation test used the cumulative CO_2 absorbed by the KOH that had been placed in the setup of desiccator jar. As a control measure, there was an extra setup of the KOH in a desiccator jar without a nanocomposite sample to determine the amount of CO_2 in the desiccator. This amount was subtracted from the CNF composite results to

give the actual sample biodegradation.

The amount of CO_2 evolved was determined at intervals of 14 days over a period of a 70-day. Table 1 is a summary of the amount of CO_2 evolved during the biodegradation of 0.2 wt% CNF nanocomposite samples and the control set up. Table 2 is the amount of CO_2 of the individual samples minus the control set up CO_2 value. Carbon dioxide evolved was determined by multiplying the no. of moles of HCl used in titration by 22 (0.5 of MM of CO_2).

Table 1. Carbon Dioxide gas (mg) evolved by nanocomposites, blank and the control set up.

Sample	14 days	28 days	42 days	56 days	70 days
Control set up	21.56	30.58	18.96	23.32	15.18
Dodecyl CNC	24.21	36.20	28.12	33.61	15.41
Butyl CNC	35.22	35.24	39.61	42.42	15.48
Reference blank	39.63	37.42	46.21	38.42	22.63

Table 2. Carbon Dioxide gas (mg) evolved by nanocomposites and blank less the control values.

Sample	14 days	28 days	42 days	56 days	70 days
Dodecyl CNC	2.65	5.62	9.16	10.29	0.23
Butyl CNC	13.66	4.66	20.65	19.1	0.3
Reference blank	18.07	6.84	27.25	15.1	7.45

The CO₂ evolved over the period was cumulatively added together and the data is summarized in table 3. These amounts were plotted against time for degradation as shown in Figure 5. The results show that CO₂ produced at the start of the tests varied across the samples, with the reference blank sample having the highest from day 1 to 70 days. The biodegradation results indicate that the reference blank sample had the highest degradation rate throughout the study, while the nanocomposites containing functionalized CNFs exhibited a decreased degradation rate. This is likely due to increased polymer crystallinity caused by the addition of the nanofibers [2].

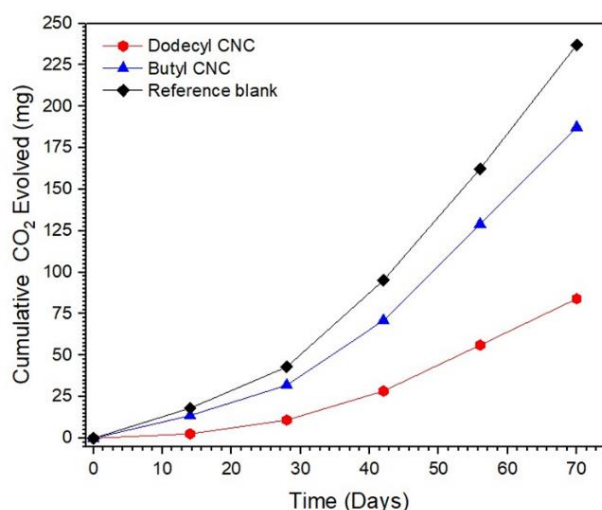
From the results, the butyl nanocomposite emitted more CO₂ compared to the dodecyl nanocomposites. The findings suggests that the butyl nanocomposite biodegraded at a faster rate than the dodecyl nanocomposite. This is attributed to the structure differences between the butyl and dodecyl which affects the adhesion of the two molecules. The long straight chain (dodecyl) degraded slower compared to the short straight chain of the butyl moiety because of the stronger bonds comprising both covalent and hydrogen bonds from the long chain [25]. The butyl and dodecyl CNF composites CO₂ evolution were ~1.3 and 2.6 times less than that of the reference blank sample.

The rates of CO₂ evolution of the nanocomposites were recorded as ~1mg/day for the butyl and ~0.6 mg/day for the

dodecyl, both were slower than the reference blank rate of ~1.3 mg/day taken for 56 days. Beyond 56 days, the CNF composite samples showed a significant decrease in the rate of evolution of CO₂ whereas the control showed a decreased rate of 0.5 mg/day. These observations indicate that the presence of functionalized CNF slows down the rate of biodegradation of the composites.

Table 3. Cumulative amount (mg) of Carbon dioxide gas evolved by the nanocomposite.

Sample	14 days	28 days	42 days	56 days	70 days
Dodecyl CNC	2.65	8.27	17.48	27.72	27.95
Butyl CNC	13.66	18.32	38.97	58.07	58.37
Reference blank	18.07	24.91	52.16	67.26	74.71

**Figure 5.** Cumulative Carbon Dioxide emitted by the nanocomposites.

3.3. Gravimetric Analysis

The second approach used to determine biodegradation involved measuring the mass loss at 14-day intervals over a 70-day period. The data for gravimetric tests was collected co-currently with the CO₂ evolved data. A summary of change in mass Δm data of the samples over the 70 days is presented in Table 4.

Table 4. Change in mass of nanocomposites containing functionalized carbon nanofiber.

Sample	M ₀	M _s -14 days	M _s -28 days	M _s -42 days	M _s -56 days	M _s -70 days
Dodecyl CNC	0.4995	0.4441	0.4331	0.3911	0.3566	0.3282
Butyl CNC	0.5009	0.4540	0.4442	0.3831	0.3496	0.3216
Ref. Blank	0.5090	0.4765	0.4321	0.3418	0.3291	0.3099

The percentage loss in mass was calculated using equation (6) below

$$\% \text{Mass loss} = \frac{M_0 - M_s}{M_0} \times 100 \quad (6)$$

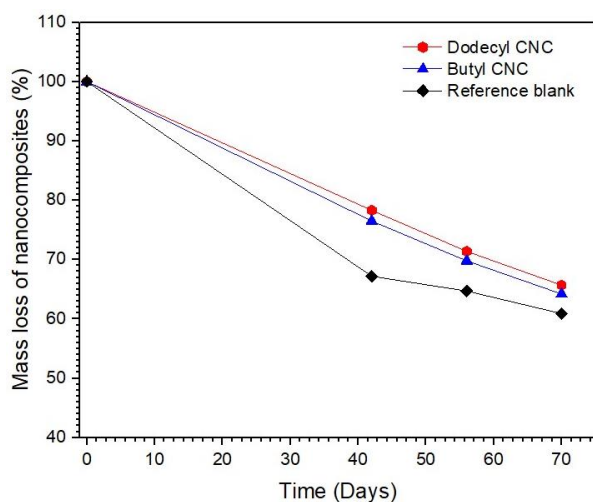
Where M₀ = initial mass of the sample before exposure

M_s = mass of the sample after a specific time exposure to biodegradation conditions.

The results were converted into percentage mass remaining at regular intervals until 70 days as shown in table 5, the values were then plotted in a graph as depicted in figure 6.

Table 5. Percentage mass loss of nanocomposites with functionalized carbon nanofiber.

Sample	14 days	28 days	42 days	56 days	70 days
Dodecyl CNC	88.9%	86.7%	78.3%	71.4%	65.7%
Butyl CNC	90.6%	88.7%	76.5%)	69.8%)	64.2%
Reference Blank	93.8	84.9%	67.2%	64.7%	60.9%

**Figure 6.** A plot of percentage mass remaining versus time.

The dodecyl and butyl nanocomposites had 65.7% and 64.2% remaining mass compared to the reference blank that had a 60.9%. The rate of loss of mass per day of butyl and dodecyl were ~0.53 and ~0.6 wt%/day compared to the control which was ~0.74 wt%/day for up to 56 days. These results generally indicate that the presence of functionalized CNF slows down the

rate of biodegradation similar to the findings of the CO₂ evolution results. A lower percentage of remaining mass indicates a higher degradation rate, and vice versa. Based on this data, the samples can be ranked from highest to lowest degradation as follows for up to 70 days: reference blank > butyl > dodecyl. The degradation rate of the nanocomposite is inversely proportional to the level of crystallinity [26]. This suggests that dodecyl moieties form more crystalline nanocomposites, which are less biodegradable, while butyl moieties form less crystalline nanocomposites with more amorphous zones, making them more susceptible to biodegradation [26]. The degradation rates by loss of mass is consistent with CO₂ emission results whereby the blank degrades faster than those of butyl > dodecyl with a comparable degradation pattern.

3.4. Extrapolation of Degradation Time for Nanocomposite Sample

An extrapolation of the estimated time taken for each sample to degrade to more than 99% was determined using the rates of degradation from the gravimetric degradation data for the three CNF nanocomposites and the reference blank.

The rate of degradation (R_D) of each sample over the 70-day period was determined by dividing the overall change in mass of the sample over the time period of the experiment, using the formula

$$R_D = -\frac{dM}{dt} \quad (7)$$

Where M = mass of the sample undergoing biodegradation,
t = time taken for the biodegradation.

The results are summarized in Table 6 below.

Table 6. Rate of degradation of nanocomposites with functionalized carbon nanofibers after 70 days.

Sample	M _i	M _s	Δ mass (g)	R _D = ΔM / t
Dodecyl CNC	0.4995	0.3284	0.1711	0.00244
Butyl CNC	0.5009	0.3215	0.1794	0.00256
Reference	0.5090	0.3101	0.1989	0.00284

The R_D values were then used in equation 8 below to determine the extrapolated time (t_d) for the degradation of the CNF nanocomposites and blank to approximately 99% [7].

$$t_d = \frac{M_0}{k_d \rho SA} \quad (8)$$

Where, M₀ - Initial mass of sample before degradation; k_d

-degradation constant; ρ - density; SA - surface area.

Assuming a first-order reaction and a consistent surface area (SA) for the samples.

(all samples were 2 cm x 1 cm x 0.031 cm), the estimated time for each sample to degrade to less than 1% of its original mass is shown in Table 7.

Table 7. Extrapolation period the nanocomposite will stay in the environment.

Sample	M ₀ (g)	R _D (g/day)	SA (cm ²)	ρ (g/cm ³)	K _d (cm/day)	t _d (day)
Dodecyl CNC	0.4995	0.00244	4.186	1.964	0.00029679	204.71
Butyl CNC	0.5009	0.00256	4.186	1.641	0.000372677	195.66
Reference	0.509	0.00284	4.186	1.41	0.000481172	179.23

Using the cumulative R_D (degradation rates), the time taken for each sample to degrade to less than 1% (t_d) was determined, and it showed that dodecyl (~204 days) remained in the environment longer than the butyl (~195 days) and the blank (~179 days) with the least stay in the environment. This corresponds to their degradation rates. It has also showed that the different moieties affect the degradation of the samples differently, with the dodecyl having a higher effect (slower rate) compared to the butyl moiety when used in functionalization of the CNFs.

4. Conclusion

The research shows that adding, butyl, and dodecyl alkyl groups to carbon nanofibers worked well. The incorporation of functionalized nanofibers into nanocomposites significantly alters their biodegradability. The study generally establishes that the incorporation of functionalized nanofibers into nanocomposites decreases their rate of biodegradation

when monitoring carbon dioxide emission and loss of sample weight techniques. However, the net effects of change in mechanical properties and increased applications somehow compensates for the slightly longer lifespan of the nanocomposites. This effect is most pronounced in the case of butyl functionalization, an increase in the wt% of the functionalized carbon nanofiber also shows a slight lower rate of biodegradation maybe again attributable to an increase in mechanical strength of the nanocomposite as the % of filler is increased.

Abbreviations

CA	Cellulose Acetate
CNF	Carbon Nanofibers
CTAB	Cetyltrimethylammonium Bromide
EDS	Energy Dispersive Spectroscopy
PTFE	Polytetrafluoroethylene
PMMA	Poly Methylmethacrylate

SA	Surface Area
SEM	Scanning Electron Microscopy
SSDR	Specific Surface Degradation Rate

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Author Contributions

Situma Stephen Mukhebi: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing

James Owour: Data curation, Formal Analysis, Investigation, Methodology, Validation, Writing – review & editing

Geoffrey Otieno: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing

Austin Ochieng Aluoch: Data curation, Formal Analysis, Project administration, Supervision, Writing – review & editing

Dickson Mubera Andala: Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Biswal, T., BadJena, S. K., & Pradhan, D. (2020). Synthesis of polymer composite materials and their biomedical applications. *Materials Today: Proceedings*, 30, 305-315. <https://doi.org/10.1016/j.matpr.2020.01.567>
- [2] Goodwin, D. G., Boyer, I., Devahif, T., Gao, C., Frank, B. P., Lu, X., Kuwama, L., Gordon, T. B., Wang, J., Ranville, J. F., Bouwer, E. J., & Fairbrother, D. H. (2018). Biodegradation of Carbon Nanotube/Polymer Nanocomposites using a Monoculture. *Environmental Science & Technology*, 52(1), 40-51. <https://doi.org/10.1021/acs.est.7b02062>
- [3] Kikku Fukushima et al. (2009), Biodegradation of poly (lactic acid) and its nanocomposites, *Polymer Degradation and Stability* 94 1646-1655, <https://doi.org/10.1016/j.polymdegradstab.2009.07.001>
- [4] Hoshino, A., Tsuji, M., Ito, M., Momochi, M., Mizutani, A., Takakuwa, K., Higo, S., Sawada, H., & Uematsu, S. (2003). Study of the Aerobic Biodegradability of Plastic Materials under Controlled Compost. In E. Chiellini & R. Solaro (Eds.), *Biodegradable Polymers and Plastics* (pp. 47-54). Springer US. https://doi.org/10.1007/978-1-4419-9240-6_3
- [5] Roy, S. B., Shit, S. C., Sengupta, R. A., & Shukla, P. R. (2015). Biodegradability studies of bio-composites of polypropylene reinforced by potato starch. *Int J Innov Res Sci Eng Technol*, 4(3), 1120-30. <https://doi.org/10.15680/IJIRSET.2015.0403066>
- [6] Sanchez-Garcia, M. D., Lagaron, J. M., & Hoa, S. V. (2010). Effect of addition of carbon nanofibers and carbon nanotubes on properties of thermoplastic biopolymers. *Composites Science and Technology*, 70(7), 1095-1105. <https://doi.org/10.1016/j.compscitech.2010.02.015>
- [7] Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*, 8(9), 3494-3511. <https://doi.org/10.1021/acssuschemeng.9b06635>
- [8] Doppalapudi, S., Jain, A., Khan, W. and Domb, A. J. (2014), Biodegradable polymers-an overview[†]. *Polym. Adv. Technol.*, 25: 427-435. <https://doi.org/10.1002/pat.3305>
- [9] Bonilla, J.; Sobral, P. (2020) Disintegrability under composting conditions of films based on gelatin, chitosan and/or sodium caseinate containing boldo-of-Chile leaf extract. *Int. J. Biol. Macromol.*, 151, 178-185, <https://doi.org/10.1016/j.ijbiomac.2020.02.051>
- [10] Karlsson, T. M., Hasselöv, M., & Jakubowicz, I. (2018). Influence of Thermo oxidative degradation on the in-situ fate of polyethylene in temperate coastal waters. *Marine Pollution Bulletin*, 135, 187-194. <https://doi.org/10.1016/j.marpolbul.2018.07.015>
- [11] Fatimah Alshehrei, (2017): "Biodegradation of Synthetic and Natural Plastic by Microorganisms." *Journal of Applied & Environmental Microbiology*, vol. 5, no. 1 8-19. <https://doi.org/10.12691/jaem-5-1-2>
- [12] Agamuthu, P.; Faizura, P. N (2005). Biodegradability of Degradable Plastic Waste. *Waste Manage. Res.*, 23(2), 95-100, <https://doi.org/10.1177/0734242X05051045>
- [13] Bernstein, R.; Derzon, D. K.; Gillen, K. T. (2005). Nylon 6.6 Accelerated Aging Studies: Thermal-Oxidative Degradation and Its Interaction with Hydrolysis. *Polym. Degrad. Stab.*, 88(3), 480-488, <https://doi.org/10.1016/j.polymdegradstab.2004.11.020>
- [14] Zaghdoudi, M., Kämmling, A., Jaunich, M., & Wolff, D. (2020). Erroneous or Arrhenius: A degradation rate-based model for EPDM during homogeneous ageing. *Polymers*, 12(9), 2152 <https://doi.org/10.3390/polym12092152>
- [15] Selene Chinaglia et al. 2018: Polymer Degradation and Stability 147 237-244 <https://doi.org/10.1016/j.polymdegradstab.2017.12.011>

- [16] Othman, S. H.; Ronzi, N. D. A.; Shapi'i, R. A.; Dun, M.; Ariffin, S. H.; Mohammed, M. A. P. (2023). Biodegradability of Starch Nanocomposite Films Containing Different Concentrations of Chitosan Nanoparticles in Compost and Planting Soils. *Coatings*, 13, 777. <https://doi.org/10.3390/coatings13040777>
- [17] Tamada, J. A.; Langer, R. (1993). Erosion Kinetics of Hydrolytically Degradable Polymers. *Proc. Natl. Acad. Sci. U. S. A.*, 90(2), 552-556. <https://doi.org/10.1073/pnas.90.2.552>
- [18] Sharon, C.; Sharon, M. (2017). Studies on Biodegradation of Polyethylene Terephthalate: A Synthetic Polymer. *J. Microbiol. Biotechnol. Res.*, 2(2), 248-257, <http://scholarsresearchlibrary.com/archive.html>
- [19] Kausar, A., & Bocchetta, P. (2022). Poly (methyl methacrylate) nanocomposite foams reinforced with carbon and inorganic nanoparticles State-of-the-art. *Journal of Composites Science*, 6(5), 129, <https://doi.org/10.3390/jcs6050129>
- [20] Liang, F., Sadana, A. K., Peera, A., Chattopadhyay, J., Gu, Z., Hauge, R. H., & Billups, W. E. (2004). A Convenient Route to Functionalized Carbon Nanotubes. *Nano Letters*, 4(7), 1257-1260. <https://doi.org/10.1021/nl049428c>
- [21] Vatansever, A., Inan, T. Y., Dogan, H., & Sirkecioglu, A. (2015). Synthesis of poly butyl acrylate - co - methyl methacrylate/montmorillonite waterborne nanocomposite via semi-batch emulsion polymerization. *Journal of Applied Polymer Science*, 132(32), app. 42373. <https://doi.org/10.1002/app.42373>
- [22] Murali, A., Ramkumar, S. C., Haridharan, N., Mohana, S., Samanta, D., & Jaisankar, S. N. (2020). Multifunctional properties of acetaminophen immobilized polymer nanohybrid composites. *SN Applied Sciences*, 2(7), 1313. <https://doi.org/10.1007/s42452-020-3059-7>
- [23] Eubeler, J. P., Zok, S., Bernhard, M., & Knepper, T. P. (2009). Environmental biodegradation of synthetic polymers I. Test methodologies and procedures. *TrAC Trends in Analytical Chemistry*, 28(9), 1057-1072. <https://doi.org/10.1016/j.trac.2009.06.007>
- [24] Cindradewi, A. W., Bandi, R., Park, C.-W., Park, J.-S., Lee, E.-A., Kim, J.-K., Kwon, G.-J., Han, S.-Y., & Lee, S.-H. (2021). Preparation and characterization of cellulose acetate film reinforced with cellulose nanofibril. *Polymers*, 13(17), 2990, <https://doi.org/10.3390/polym13172990>
- [25] Singh, N. K.; Purkayastha, B. D.; Roy, J. K.; Banik, R. M.; Yashpal, M.; Singh, G.; Malik, S.; Maiti, P. (2009) Nanoparticle-induced controlled biodegradation and its mechanism in poly (ϵ -caprolactone) *ACS Appl. Mater. Interfaces*, 2(1), 69-81, <https://doi.org/10.1021/am900584r>
- [26] Wang, S., Song, C., Chen, G., Guo, T., Liu, J., Zhang, B., & Takeuchi, S. (2005). Characteristics and biodegradation properties of poly (3-hydroxybutyrate-co-3-hydroxyvalerate)/organophilic montmorillonite (PHBV/OMMT) nanocomposite. *Polymer Degradation and Stability*, 87(1), 69-76. <https://doi.org/10.1016/j.polymdegradstab.2004.07.008>