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Effect of crosslinking on nanocellulose superabsorbent biodegradability

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ABSTRACT

Superabsorbent polymer (SAP) is an excellent material to absorb and retain a wide range of fluids inside its structure, making it desirable to engineer advanced applications. However, commercial SAPs are products of the petrochemistry, and their non-biodegradability and end of life are significant environmental issue. In this study, we have developed TEMPO oxidized nanocellulose superabsorbent and quantified the effect of crosslinking on biodegradation in soil under enzymatic (cellulase) assisted conditions. CO_2 emission shows that both type of SAP emits similar amount of CO_2. Hydrolysis of residual SAPs in soil after specific time intervals shows that chemically crosslinked SAP degrades to a higher extent (~56%) compared to neat nanocellulose SAP (~41%). However, without enzyme, their degradation are similar (~8–12%) and much lower than under enzymatic condition. These results suggest that nanocellulose SAPs: both neat and crosslinked -can easily and rapidly be degraded at home or in the compost of the garden under proper enzymatic assisted conditions.

1. Introduction

Superabsorbent materials are three dimensional polymeric networks able to absorb and retain large volumes of water and aqueous solutions inside their structure (Zohuriaan-Mehr & Kabiri, 2008). These water absorbing polymers swell considerably, even under load (Yu et al., 2011; Zohuriaan-Mehr et al., 2010) because of their hydrophilic functional groups (Behera & Mahanwar, 2020). Superabsorbent polymers (SAPs) can be divided into two groups based on their origin: (i) natural SAP: polysaccharide and polypeptide based; and (ii) synthetic SAP: acrylic, vinyl acetate or polyethylene glycol based (Okay, 2009; Sadeghi, 2008). Most commercial SAPs are synthetic, petrochemically derived, environmentally persistent (Passauer et al., 2015). Sodium polyacrylate based SAPs are the most commonly used commercial material, predominantly in disposable diapers and feminine hygiene products. Globally, over 2 million metric tons of acrylate SAP is being produced annually, of which disposable diapers account for 74% (Chazovachii et al., 2021). Acrylate based SAPs are non-biodegradable and non-renewable, and their environmental persistence contributes to pollution and global warming. These detrimental environmental effects have increased the thirst for sustainable, renewable, biodegradable superabsorbent based on polysaccharide.

Biodegradable SAPs are attractive for their abundancy, low cost and non-toxicity. Recent literature describes the superabsorbent performance of several biodegradable polymers, such as cellulose, chitosan, starch, rice husk, raw bran and tulips (Qureshi et al., 2020). Among those, cellulose is of special interest due to its high water holding capacity, abundance, ease of functionalization, full biodegradability, biocompatibility and non-toxicity (Mondal, 2019). TEMPO oxidized nanocellulose SAP has been engineered for different applications such as packaging, baby diaper, agriculture and biomedical (Barajas-Ledesma et al., 2021; Curvello et al., 2019; Hossain et al., 2020; L. Mendoza et al., 2019). High surface charge TEMPO-periodate oxidized nanocellulose produces SAP of high absorption capacity and tunable absorption kinetics (L. Hossain et al., 2021; D. J. Mendoza et al., 2019). Recent development on cellulose superabsorbent has demonstrated that cellulose-based SAP can be engineered specifically to suit many specific applications (Ciolacu et al., 2016; López Durán et al., 2018; Wendler et al., 2012).

In spite of its widespread use, the biodegradability of Acrylate SAP and even natural SAP have been very poorly and inconsistently characterized. Further, natural based SAP typically requires crosslinking to achieve properties similar to acrylate SAPs. A growing concern is how this crosslinking might affect their biodegradability. To address this gap, biodegradability of neat and crosslinked nanocellulose SAP is quantified in this study. There are many studies using various methods to measure biodegradation and there is a lack of uniformity and standardization for comparison. Soil burial degradation assay is one of the most common tests to quantify the degradation rate. Water hyacinth cellulose-graft-poly(ammonium acrylate-co-acrylic acid) polymer SAP lost 25% of its

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initial mass after 14 days in garden soil (Rop et al., 2019). Maleylated cellulose-g-poly(acrylic acid) SAP lost 47% of its initial mass after 150 days in soil (Sawut et al., 2014). Biodegradation can also be measured by quantifying biological oxygen demand (BOD) or oxygen consumption over time. Chitin based SAP showed almost complete degradation based on BOD after 20 days (Yoshimura et al., 2005). There is ISO standard (ISO 14,855–1:2012) to determine the aerobic biodegradability of plastic materials under controlled conditions by analyzing evolved CO_2 and the sample size and shape (Kim et al., 2003). However, these are indirect methods to determine biodegradation by weighing leftover sample mass. Here, we quantify the leftover mass by sample hydrolysis and glucose measurement using high-performance liquid chromatography.

Degradation of cellulose can be accelerated by using enzymes or fertilizer (Barajas et al., 2021; Chmolowska, Hamda & Laskowski, 2017). Cellulase is the specific enzyme for cellulose degradation. The main factors affecting the enzymatic cellulose degradation process include: substrate composition, crystallinity, hydrophobicity, accessibility (porosity/structure), temperature, pH, nature of the enzymes, and inhibition effects of reaction products (Deng, 1994). Enzymatic degradation is slower for crystalline and hydrophobic materials (Yoshida et al., 2008; Zambrano, Pawlak & Venditti, 2020). Accessibility of the material for enzyme is another crucial parameter. For cellulosic materials, accessibility of cellulase is around 90% through the internal specific pores (Dutta & Chakraborty, 2016). Cellulase adsorption on the outer surface of substrate has a small contribution in the overall adsorption (Baig, 2020). Substrate structure as well as reaction environment, including the enzyme type, thus affect the enzymatic degradation of cellulose.

Enzymatic degradation of cellulose is faster compared to that without enzyme and is typically achieved in solution. However, in nature, there is an array of microorganisms producing cellulases in the soil which can naturally degrade the solid product over time (López-Mondéjar et al., 2016; Soares et al., 2012). Many of the household waste which contains SAP are in solid form, for example, disposing baby diapers or the absorbent pad in meat packaging. Degrading such products at home in a shorter time span is beneficial to the environment and minimize the use of fertilizer. The biodegradation of these household products under enzymatic condition is poorly characterized. Moreover, the effect of crosslinking on the superabsorbent enzymatic degradation has not been investigated. The objective of this study is to quantify biodegradation rate of cellulose superabsorbent in sandy soils under enzymatic assisted condition to quantify enzyme and crosslinking effect. Both neat and crosslinked SAPs are analyzed for 6 days to quantify the degradation rate and microbial activity. This study can pave the way to consumable SAPs degradation in just a few days in the garden. Moreover, the rapid degradation of crosslinked SAP can further guide product development with strong chemical crosslinking to engineer properties.

2. Methodology

2.1. Materials

Bleached Eucalyptus Kraft (BEK) pulp was provided by Australian Paper, Maryvale, Australia. 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) and sodium bromide (NaBr) were purchased from Sigma Aldrich. 12 w/v% sodium hypochlorite (NaClO) was purchased from ThermoFisher Scientific. Sodium hydroxide (NaOH) and hydrochloric acid (HCl) were purchased from Merck and ACL Laboratories respectively and diluted for solution as required. Cellulase from *Trichoderma reesei* was purchased from Merck.

Soil was collected from a vegetable farm located in Cranbourne, Victoria (38°11′6″S; 145°18′50″E). The soil was classified as a Podosol, according to the Australian Soil Classification criteria (Isbell, 2016). Soil was collected at a depth of 0 – 20 cm, air-dried and sieved to > 2 mm. A subsample of 200 g was analyzed for range of key physicochemical properties (Table S1). The analysis was conducted by Environmental Analysis Laboratories, at Southern Cross University (Environmental Analysis Laboratory, 2020), using Rayment and Lyons standard methods (Rayment, 2011).

2.2. TEMPO oxidation

TEMPO-mediated oxidation was based on a previously developed method (Saito et al., 2007). 25 g (dry weight) BEK pulp was suspended in 2500 mL of deionized water containing 0.4 g TEMPO and 2.5 g NaBr. The pH of 100 mL 12 w/v% NaClO was adjusted to 10 by the addition of 32 w/v% HCl. NaClO was added dropwise to the reaction mixture to initiate the oxidation reaction. The pH of the reaction was maintained by addition of 0.5 M NaOH dropwise throughout the reaction period of 3 h. The oxidized fiber was washed with deionized water and vacuum filtered until neutral pH was achieved, and then stored at 4 °C.

2.3. Production of oxidized nanocellulose hydrogel

Oxidized pulp was dispersed using an electric hand mixer (ANCO 500) in deionized water at the desired concentration (0.5 g dry fiber in 100 g suspension) and homogenized for two passes through a high-pressure homogenizer (GEA Niro Soavi Homogenizer Panda) at 1000 bar to produce oxidized nanocellulose hydrogel.

2.4. Solids concentration

The solids concentration of all samples (i.e. hydrogel or pulp) was determined through oven drying. The sample was weighed before (w_i) and after (w_d) drying. Sample moisture was removed by drying in an oven (Thermoline BTC 9090) at 105 °C for at least 6 h. The solids content was calculated as:

$$Solid\ content\ (\%) = \frac{w_d}{w_i} \times 100\%$$

2.5. Chemical crosslinking

Hexa methyl diamine (HMDA) was dissolved in deionized water at a concentration of 0.45 g/mL. The nanocellulose hydrogel from Section 2.3 was mixed with this HMDA solution at a ratio of 1:1 (COO^-:NH_2) in presence of EDC/NHS and incubated at room temperature for 16 h to produce crosslinked oxidized nanocellulose hydrogel.

2.6. Preparation of nanocellulose SAPs

Nanocellulose SAP was prepared by spreading 12 g of neat or crosslinked oxidized nanocellulose hydrogel evenly over the base of a 50 mm petri dish and freezing the sample at −86 °C, then freeze-drying (Christ Alpha 2–4 LD Plus) for 2 days to produce neat and crosslinked SAPs.

2.7. ATR-FTIR

ATR-FTIR spectrometry was performed using an Agilent Cary 630 FTIR Spectrometer to confirm chemical crosslinking in freeze-dried SAP samples.

2.8. Microbial activity

Samples were prepared by mixing the SAP at the application rate of 0.25 wt% and 0.5 wt% into 50 g of soil. Deionized water with enzyme was then added to reach 60% moisture content. Two concentrations of enzyme (High Enzyme, HE = 100 μL enzyme / 7 mL water and Low Enzyme, LE = 50 μL enzyme / 7 mL water) were prepared in deionized water. Samples were incubated at 35 °C and 80% relative humidity in a temperature/humidity control cabinet (Thermoline L + M – 150-GD).

Daily gas samples over 6 days were collected using the method adapted from van Zwieten, Kimber (van Zwieten et al., 2010). Briefly, soil treatments in containers with known volume and basal area were sealed and gasses were allowed to accumulate for 20 min. The gasses were then collected from the sealed containers using an airtight syringe (SGE Analytical Scientific) and inserted into pre-evacuated 12 mL Exetainers ® vials through a septum. Gas samples were analyzed for CO_2 using an Agilent Technologies 7890A Gas Chromatograph with Thermal Conductivity Detector (GC-TCD) and GC-Flame Ionization Detector (FID). The detector temperature was 250 °C. Helium was used as the carrier gas at 21 mL/min. The temperature of the column and oven was 60 °C.

The flux rate, F_{CO2} (mg CO_2 / m^2h) was calculated using the following equation:

$$F_{CO2} = \frac{b \times V_{CH} \times MW_{CO2} \times 60 \times 10^6}{A_{CH} \times MV_{corr} \times 10^9}$$

Where, b = CO_2 concentration measured in ppm/min
V_{CH} = measuring chamber volume
MW_{CO2} = molecular weight of CO_2
A_{CH} = basal area of measuring chamber
MV_{corr} = temperature corrected molecular weight = 0.02241 × $\frac{273.15+T}{273.15}$, T = air temperature

2.9. Biodegradation

Samples were prepared by mixing the 0.25 wt% SAP with dry soil to prepare 10 g of soil treatment. HE (100 μL enzyme / 7 mL DI water) or LE (50 μL enzyme / 7 mL DI water) enzyme solutions were added to reach 60% moisture content. A control treatment without any SAP was also carried out both for HE and LE. Samples were incubated at 35 °C and 80% relative humidity in a temperature/humidity control cabinet (Thermoline L + M – 150-GD). At appropriate sampling time points (day 2, 4, 6) samples were dried in an oven at 60 °C and stored frozen at −20 °C until required. Three replicates for each condition were conducted.

An acid digestion method adapted from Sluiter, Hames (Sluiter et al., 2008) was used to quantify biodegradation by hydrolyzing residual cellulose to glucose and glucuronic acid, which can be measured by chromatography. In brief, 3 mL of 72% sulphuric acid was added to 5 g of soil treatment. The treatment was then placed on a hot plate at 30 °C and incubated for 60 min. The mixture was stirred every 5 to 10 min to ensure even acid – treatment contact. Samples were then diluted to 4% sulphuric acid by adding 84 mL of water and autoclaved for 30 min at 121 °C. After cooling at room temperature, treatments were filtered, and the supernatant was neutralized to a pH 5 – 6 using calcium carbonate. Upon neutralization, treatments were then centrifuged at 10,000 rpm for 5 min. The supernatant was collected and analyzed through high performance liquid chromatography (HPLC) using a BioRad Amminex HPX-87H column, 0.005 M sulfuric acid as mobile phase, with a refractive index detector at a temperature of 60 °C and a flow rate of 0.4 mL/min.

3. Results

TEMPO oxidation of cellulose fibers produces nanofibers (> 1μm long and > 5 nm wide) (Mendoza et al., 2020) which was homogenized and freeze-dried to produce nanocellulose SAP. Neat and chemically crosslinked nanocellulose SAP were characterized by FTIR to confirm crosslinking. The SEM images of neat and crosslinked samples are given in Figure S1 (L. Hossain et al., 2021). The microbial activity and biodegradation rate of neat and chemically crosslinked nanocellulose SAPs were analyzed in soil under enzyme (cellulase) assisted conditions. Microbial activity was determined by CO_2 vol evolved daily from day 1 to day 6. Biodegradation rate was quantified by acid hydrolysis for day 2, 4 and 6.

3.1. FTIR

FTIR spectra of the neat and crosslinked oxidized nanocellulose SAP with HMDA were measured. Fig. 1. shows that neat oxidized nanocellulose SAP has a peak at 1600 cm^{-1} due to COO^-. Chemically crosslinked SAP has the expected characteristic C = O stretching at 1560 cm^{-1} due to amide bond formation between the COO^- group of nanocellulose SAP and the NH_2 group of HMDA. These results show that HMDA successfully crosslinked the oxidized nanocellulose.

3.2. Microbial activity

In general, cumulative CO_2 emission increases with time and enzyme concentration for biodegradation of both neat and crosslinked nanocellulose SAP at high and low enzyme concentrations (Fig. 2). An increase in enzyme concentration increases cumulative CO_2 emission, which indicates the soil microbial community response is higher when high concentration of enzyme is used. However, the correlation is not linear. Doubling the enzyme concentration does not result in doubling of the CO_2 emission, implying that there is a plateau effect for this parameter. For crosslinked and neat nanocellulose SAPs, the CO_2 emission is similar. There is slightly higher CO_2 emission from neat nanocellulose SAP, but the error bars overlap, indicating that the difference is not significant.

Fig. 3 shows the effect of neat and crosslinked SAP application rate on microbial activity. The results are similar in all cases, which indicates that increasing the SAP loading from 0.25% to 0.5% (wt% relative to soil) for neat and crosslinked nanocellulose SAP does not significantly affect CO_2 emissions or microbial activity.

Overall, the results indicate that individual effect of enzyme concentration is greater than the individual effects of crosslinking and SAP loading on cumulative CO_2 emission during microbial testing.

3.3. Biodegradation

Fig. 4 shows the effect of enzyme concentration and crosslinking on biodegradation; this is in terms of mg of SAPs remains in the soil after specific intervals. The degradation rate is almost constant over 6 days. Around 41% SAPs degraded in 2 days for neat SAP and 56% for crosslinked SAP with low enzyme concentration. After day 6, there is 1.51

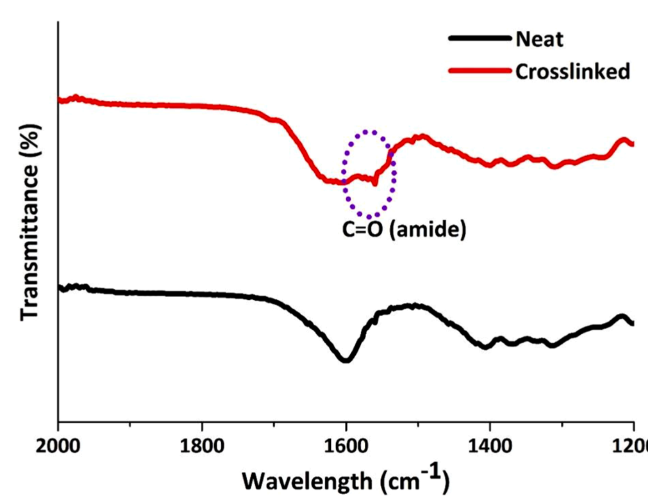

Fig. 1. FTIR spectra of nanocellulose (neat) and HMDA crosslinked nanocellulose SAPs.

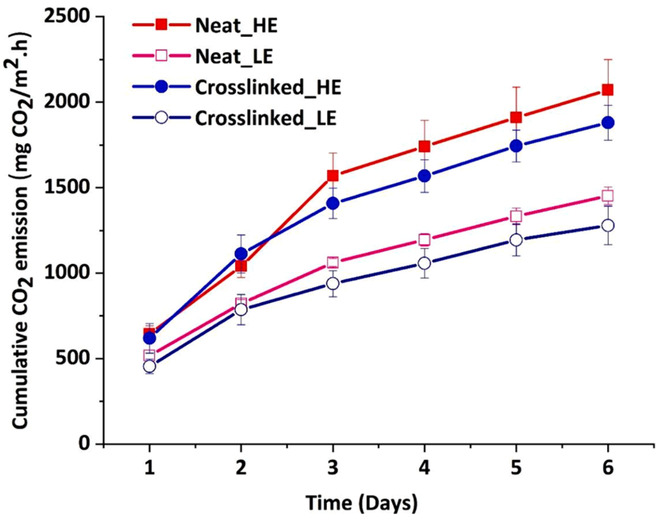

Fig. 2. Effect of enzyme concentration and crosslinking on microbial activity for neat and crosslinked nanocellulose SAP. HE indicates high enzyme concentration whereas LE refers to low enzyme concentration.

±0.08 mg and 0.90±0.21 mg nanocellulose SAP remaining in the soil for neat and crosslinked SAP with low enzyme concentration, respectively. Without enzyme the sample remaining increased to 2.29±0.18 mg for neat and 2.20±0.19 mg for crosslinked SAP while the original sample was 2.5 mg/g soil. Biodegradation rate of crosslinked nanocellulose SAP for high enzyme concentration is also higher compared to neat SAP, as seen from the lower amount of SAP remaining in the soil after day 2,4 and 6.

4. Discussion

Enzymatic degradation of neat and crosslinked nanocellulose SAPs in soil was analyzed at different enzyme and solid concentration. Nanocellulose SAP, both neat or crosslinked, degrades more than four times faster under enzymatic assisted condition compared to degradation without enzyme. The effect of crosslinking and its consequence on the biodegradation rate was evaluated by quantifying residual cellulose in soil at regular time intervals and microbial activity. Chemically crosslinked nanocellulose SAP does not reduce its biodegradation rate. Indeed, higher biodegradation rate was measured for the crosslinked nanocellulose SAP compared to that of neat SAP. The effect of solid concentrations shows no effect on microbial activity indicating the possibility of using higher solid concentration for degradation. This analysis confirms the potential and feasibility of fast degradation (~60% within 2 days) of cellulose based SAP material using enzyme assisted home compost technology.

Difference in biodegradation rate for neat and crosslinked SAP is noticed in Fig. 4. This result is analyzed based on SAP structure, enzyme accessibility and chemical composition of SAP. Cellulases are enzymatic protein macromolecules of diameter of 4–6.5 nm and 18–21.5 nm length (Bubner et al., 2012). The nanocellulose SAP has pore size bigger (micron size: few microns to few hundreds microns) than the enzyme size range (4–6.5 nm) as previously quantified (L. Hossain et al., 2021). The pores inside the nanocellulose SAPs structure are the main contributors for the accessibility (Dutta & Chakraborty, 2016) of cellulase. Here, nanocellulose SAP has micron size pores which are at least 1000 times bigger than cellulase enzyme. So, in terms of cellulase accessibility, crosslinked SAP is not creating any hinderance. Moreover, the biodegradation rate is higher for crosslinked SAP as noticed in Fig. 4. We raise the hypothesis that the nitrogen from HMDA acts as a fertilizer promoting degradation. Indeed, Jarerat et al. showed that addition of 0.1% (w/v) gelatin (which has the same -CONH groups as HMDA crosslinked SAP) with 100 mg PLA film acts as the nitrogen source resulting in increased biodegradation of PLA film by *Saccharothrix Waywayandensis* (Jarerat & Tokiwa, 2003). In our study, nanocellulose crosslinking with HMDA is done with a COO^-:NH_2 ratio = 1:1 which results in 3.64% (w/w) nitrogen of the total nanocellulose fiber present in the system. This nitrogen source is responsible for the increase in biodegradation rate of the crosslinked SAP.

Neat nanocellulose SAP biodegrades by around 8% (2.29 mg/g soil left) without enzyme, whereas with enzyme, it increases to 35–40% after 6 days for both the enzyme concentrations tested (Fig. 4). Similarly, for chemically crosslinked SAP, the degradation is around 12% (2.20 mg/g soil left) whereas with enzyme, it degrades to 56–64% after 6 days (for both enzyme concentrations) (Fig. 4). Addition of cellulases effectively accelerates the breakdown of cellulose SAP – crosslinked or not- to glucose in soils. The microbial activity determined with different solid concentrations (0.25% and 0.5% SAP in soil) does not show difference in microbe response in terms of CO_2 emission (Fig. 3), indicating that

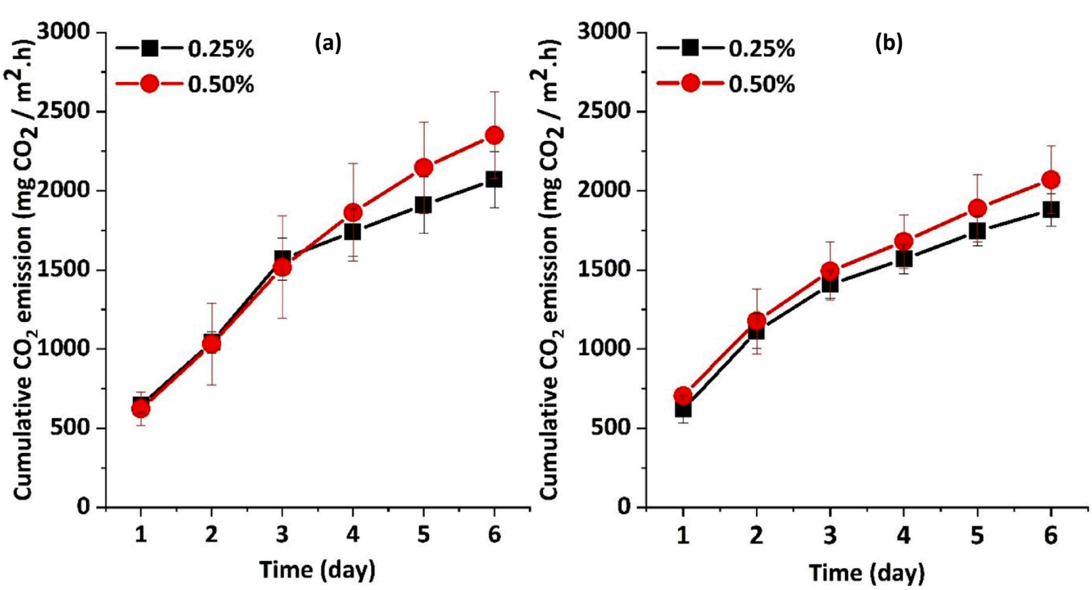

Fig. 3. Effect of nanocellulose SAP solid concentration on microbial activity with high concentration of enzyme: (a) Neat nanocellulose and (b) crosslinked nanocellulose.

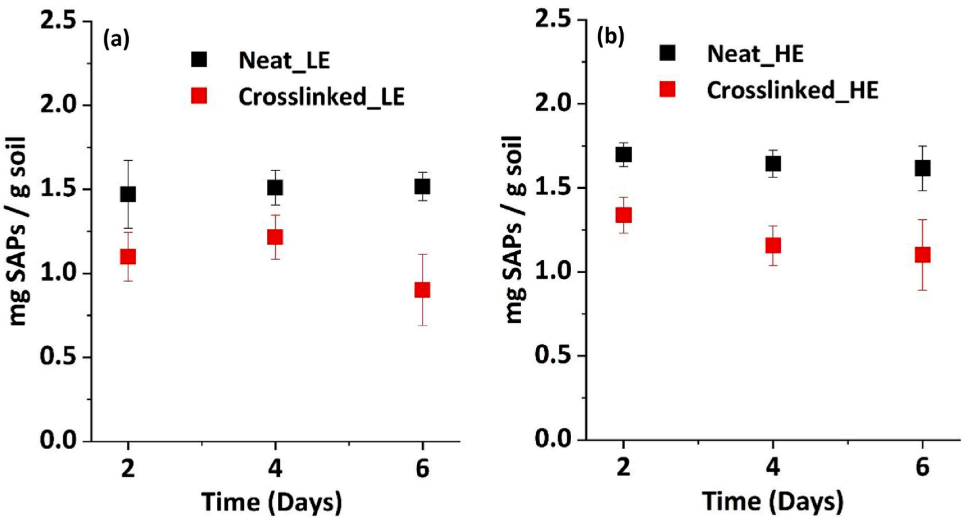

Fig. 4. Effect of enzyme concentration and crosslinking on the nanocellulose superabsorbent biodegradation in soil. The amount of superabsorbent which remained is reported: (a) low enzyme and (b) high enzyme. LE indicates low enzyme concentration whereas HE indicates high enzyme concentration. Initial sample (SAP) mass was 2.5 mg/g soil.

microbes are responding similarly for higher SAP concentration as well as confirming their higher degradability.

The degradation rate for both neat and crosslinked SAP did not change significantly after day 2 (Fig. 4). Neat and crosslinked SAP degrades around 41% and 56%, respectively, (with low enzyme concentration) after day 2; the difference is statistically significant. Enzymatic degradation depends mostly on factors such as temperature, accessibility, structure of substrate and inhibition. Temperature, humidity and moisture content were kept constant throughout the incubation period. Could product inhibition- from cellulose to cellobiose or glucose formation- affect degradation? To determine any product inhibition effect, nanocellulose SAP was mixed with cellobiose in 1:1 ratio and analyzed for its biodegradation in soil. From day 2, it is evident that biodegradation (Table S2) is not product inhibited, neither by cellobiose nor by glucose. The sample left in the soil after day 2 was 0.35±0.10 mg sample/g soil from the initial mass of 2.5 mg sample/g soil. This indicates around 79% biodegradation, confirming the absence of product inhibition. As cellobiose was added initially, its inhibition would have decreased any biodegradation, which was not the case. Instead, adding of cellobiose increases the biodegradation as part of the sample was already in the form of cellobiose- so it is rather easier for enzyme to degrade. This findings of higher degradation with initial cellobiose concentration also rules out the possibility of glucose inhibition. The insignificant difference of biodegradation rate after day 2 might therefore be due to enzyme inactivity at 35 °C after day 2 which slows down the biodegradation.

These new cellulose-based SAP can be used in baby diaper and degraded at home compost. Baby diaper contains around 33.3 wt% SAP (Itsubo et al., 2020) while the average weight of a clean diaper without urine is of 41 g (Mirabella, Castellani & Sala, 2013). Extrapolating from this study, 2.7 to 5.4 kg soil is required to degrade the SAP of one diaper (containing 13.65 g of nanocellulose SAP) at the 0.5 and 0.25% solid addition in soil, respectively. Around 41% of SAP will be degraded within 2 days when using neat SAP. However, this calculation is based on the weight of commercial SAP used in baby diaper, nanocellulose based SAP can have lower amount in baby diaper composition. Moreover, using food waste in the compost can lower the soil requirements. Additionally, our experiment was performed by hydrolyzing the soil with residual sample after specific time intervals which limited the use of higher solid concentration in soil in experimental condition. This was a model study to prove the concept. In practice, higher SAP concentration is expected. The strong sunlight and soil microbes will accelerate the SAP degradation in garden compost. Moreover, different types of enzymes will be present in a garden or urban compost.

This study indicates that nanocellulose SAP can be an adequate substitute for commercial, petro-chemical based SAP in baby diaper. The other components of diapers, such as PLA base sheet, can all be made biodegradable and have already been developed. The only problematic part is the non-renewable, non-biodegradable SAP. In this study, we have proven that renewable nanocellulose SAP can degrade by around 40 to 60% in 2 days under enzymatic assisted conditions. This study not only explores the potential of easy diaper composting, but also broadens the opportunity of using cellulose SAP for food packaging applications. For food packaging, there is already different types of sustainable packaging made of paper that can all biodegrade, except for the SAP in absorbent pad. Replacing the acrylate-based SAP with cellulose SAP enables consumers to environmentally degrade absorbent packaging using their garden compost.

5. Conclusion

TEMPO oxidized nanocellulose-based superabsorbent (SAP) was evaluated for its quick biodegradation in soil- under cellulase assisted conditions or not. Using Hexamethylene Diamine (HMDA), the objective was to measure whether chemical crosslinking affects the biodegradation of nanocellulose SAP. The effect of enzyme concentration on neat and crosslinked SAP degradation was analyzed and the microbial activity in soil at different application rates was measured.

Analysis reveals that crosslinked nanocellulose SAP is more biodegradable than the neat SAP under enzymatic assisted condition. Neat and crosslinked SAP without enzyme degrades around 8% and 12% respectively (after day 6) indicating slower degradation. When with enzyme, HMDA crosslinked nanocellulose degrades faster (around 56% degrades after day 2) than the neat SAP (around 40% degrades after day 2). This finding is due to the nitrogen source available in the HMDA structure which increases the degradation rate.

Both neat and chemically crosslinked SAPs showed similar microbial activity (in terms of CO_2 emission) indicating similar microbe response. The microbial activity of nanocellulose SAP increases with the increase of enzyme concentration; however, increasing the SAPs application rate does not affect the microbial activity. Microbial activity also strongly depends on the nutrient availability and initial microbial biomass availability in the soil (Cui et al., 2021; Jiménez et al., 2019). So, high enzyme (cellulase) concentration increases microbial activity for both types of SAPs.

This study quantifies the effect of cellulase for different types of nanocellulose SAPs in terms of SAP structure-enzyme accessibility. Rapid biodegradation of chemically crosslinked SAP (56%) within 2 days facilitates the use of crosslinked SAP without any biodegradability issues. This study shows crosslinked nanocellulose SAP is suitable for home composting, and could pave the way to fully compostable diapers, hygiene products and food packaging applications by replacing the non-biodegradable, synthetic, acrylate-based SAPs currently used in these products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.carpta.2022.100199.

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