PLA-Chitosan Composites as Sustainable Alternatives for Menstrual Pads

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Abstract

Polyethylene-based menstrual pads take centuries to biodegrade, contributing significant environmental waste while posing health risks for users. Fortunately, alternative polymers are available to replace polyethylene in menstrual pads. This research focuses on creating a composite of two promising polymers, Polylactic Acid (PLA) and Chitosan, as an alternative material to polyethylene-based menstrual pads. Both polymers are biodegradable and biocompatible, with chitosan being uniquely antimicrobial, presenting them as ideal materials for eco-friendly menstrual pads. The polymer blending technique, solvent blending, was utilized to mix PLA and Chitosan solutions in five different ratios. The solutions were placed into an air dryer for solvent evaporation, leaving behind thin film composites. A comprehensive analysis was conducted to assess the suitability of these materials through assessing its surface morphology, mechanical properties, water absorption, antimicrobial properties, and biodegradation. The findings demonstrated profound improvements in flexibility and tensile strength, water absorption, antimicrobial properties, and biodegradation. In comparison to polyethylene-based menstrual pads, this composite material can degrade in a few years, drastically improving the biodegradability period. These results offer valuable insights into the feasibility of PLA-chitosan composites for sustainable and health-conscious menstrual products. More importantly, a PLA-chitosan-based menstrual pad allows women to use a safer, eco-friendly product without concerns about health risks from synthetic materials.

Keywords: Menstrual Pads, Polylactic Acid, Chitosan, Biodegradable, Biocompatible, Antimicrobial, Composite, Solvent Blending

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1. INTRODUCTION

Today, conventional menstrual products pose as significant environmental and health challenges. Ninety percent of these menstrual pads are comprised of plastic (Fourcassier et al., 2002). Specifically, a conventional pad will generally include a polypropylene/polyethylene fiber top, a polyacrylate polymer foam core, and a back sheet with pigmented polyethylene film (Woeller & Hochwalt, 2015). Due to the long-lasting nature of those plastic polymers, each pad could take from 500 to 800 years to biodegrade, generating over 240,000 tons of plastic waste annually (Fourcassier et al., 2002). Other than environmental concerns, the materials used in conventional sanitary pads raise serious issues regarding human health. One of the most prominent substances, polyethylene, is cancer causing for the human body and can result in negative effects such as skin diseases, alteration of vaginal keratinocyte cytoskeleton structure, and cell stress and inflammation (Dhaka et al., 2022; Pontecorvi et al., 2023). Moreover, harmful chemicals including phthalate, dioxin, volatile organic compounds (VOCs), lead, and mercury contain endocrine disruptive or carcinogenic properties (Upson et al., 2022). This raises significant concerns about the potential health risks posed by these materials, emphasizing the need for safer and more body-friendly alternatives.

To address these environmental and health concerns, researchers are exploring biodegradable and biocompatible alternatives. Two alternatives that pose as promising materials are the biopolymers Polylactic Acid (PLA) and chitosan. PLA (C3H6O3)n is composed of repeating units of lactic acid and is produced from renewable resources such as corn starch or sugarcane. Through ring-opening polymerization or fermentation, lactic acid monomers are polymerized to form a biodegradable plastic (Cunha et al., 2022). The second alternative material, Chitosan (C8H13O5N)n is a linear polysaccharide of randomly distributed β-(1-4)-poly-N-acetyl-Dglucosamine. It derives from chitin from the shells of crustaceans such as shrimp and crabs (Elieh-Ali-Komi & Hambli, 2016). Both PLA and chitosan have advantageous properties for the purpose of creating a menstrual product. PLA is biodegradable, biocompatible, and requires low energy production (Farah et al., 2016). Similarly, Chitosan is biodegradable and biocompatible while possessing antimicrobial, anti-inflammatory, and wound healing properties (Aranaz et al., 2021). Polyethylene sharply contrasts these two biopolymer's properties as it is non-biodegradable, pollution inducing, and harmful to human health. When compared to the properties of one of the most commonly found material in menstrual pads, polyethylene, it is clearly evident these two polymers are more suitable as polymeric materials for menstrual pads.

Menstrual pads made from a composite of PLA and chitosan offer a practical solution in addressing both environmental sustainability and menstrual health. The biodegradable nature of PLA, combined with chitosan's antimicrobial properties, creates a material that promotes better vaginal health while naturally degrading in the environment. This approach not only reduces the risk of harmful health conditions associated with synthetic products but also aligns with the growing demand for eco-friendly personal care products, contributing to a cleaner, more sustainable planet.

The addition of chitosan to PLA is key in creating a suitable material for menstrual pads. First, PLA is naturally very brittle and rigid, thus, with the addition of chitosan, a soft material, the composite can exhibit favorable mechanical properties. Second, PLA is hydrophobic. This is not beneficial for the use of menstrual pads as they require high water absorption properties to take in large volumes of blood. Additionally, an arid environment deters key microorganisms in the process of environmental biodegradation. Fortunately, chitosan is hydrophilic, and its presence can enable the circumvention of these issues. Moreover, PLA is not antimicrobial while chitosan is naturally antimicrobial. An antimicrobial menstrual pad will be beneficial for the vaginal health and can deter developments of vaginal infections.

To create such composite, we used solvent blending to mix the two polymers. This method aims to improve material compatibility and distribution while maintaining scalability for industrial production. This process has commonly been used to nanocomposites and has been highly successful. Our research will optimize the blending process, characterize the resulting composites, and assess their suitability for menstrual product applications. The goal is to develop a material that combines PLA's biodegradability, chitosan's antimicrobial properties, and the necessary mechanical characteristics for effective menstrual products as summarized in Figure 1. If successful, this approach could lead to more sustainable and health-conscious alternatives in the feminine hygiene industry.

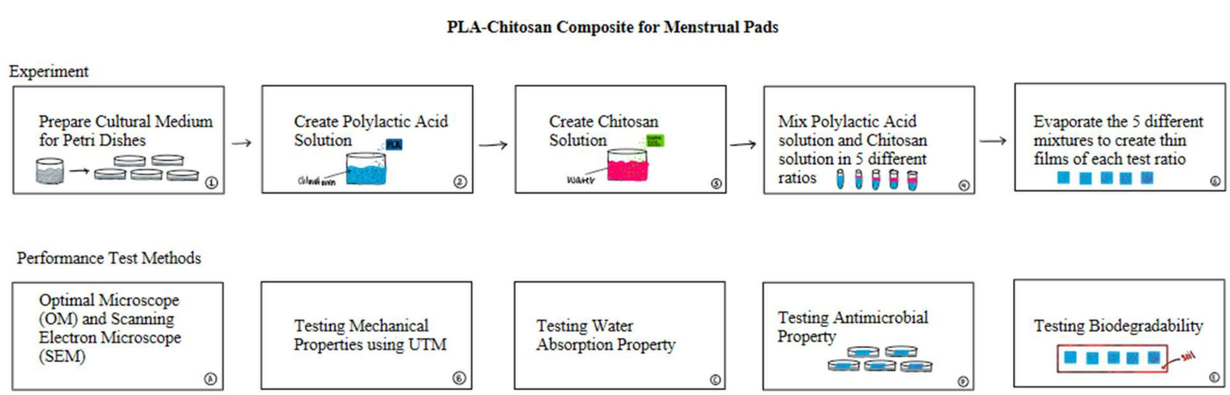

Figure 1: Preparation Process of the PLA-Chitosan Composite and Performance Test Procedures

2. METHODS

2.1 Raw Materials and Reagents

The main polymer used to create my composite is Polylactic Acid powder (PLA, NatureWorks 4032D, Mw = 50,000 g/mol) with an additive of Chitosan powder (90% deacetylated, Sigma-Aldrich). Other materials include: Dichloromethane (ASigma-Aldrich) as solvents for PLA powder; distilled water and Acetic acid (1% v/v solution) as solvents for the Chitosan powder; *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 25923) for the antimicrobial test; Garden soil for biodegradation testing (pH 6.5-7.5) for the testing of biodegradation properties.

2.2 Equipment

In my research, I used Optical Microscope (Olympus BX51), Scanning Electron Microscope (HITACHI S4800), Universal Testing Machine (Instron 5567), Electric Magnetic Mixer (500-2000 rpm capability), Laboratory Oven with controlled temperature, Automated Shaker (200 rpm capability), Incubator (37°C), Analytical Balance (0.0001g precision).

2.3 Preparation of liquid cultural medium in Petri Dish

To test the antimicrobial performance of the final composite, a cultural medium needs to be created for bacteria to grow in petri dishes. 100 milliliters of agar cultural medium is created using 1g of Tryptone, 1g of NaCl, 0.5g of Yeast Extract, 1.5g of Agar, and distilled water. These particles are mixed using an electric magnetic mixer for 30 minutes and placed in a sterilizer machine for 131° Celsius for 30 minutes. Afterwards, the mixture is poured into 10 separate petri dishes and left to solidify.

2.4 Preparation of PLA-Chitosan composites

The preparation of PLA solution: 5g of PLA powder is dissolved in dichloromethane to create a 100mL solution. *The chitosan solution was prepared* using an electric magnetic mixer for 30 minutes by mixing 2.0g of chitosan powder dissolved in distilled water with acetic acid being slowly added to create a 100mL solution. In order to ensure both the PLA and chitosan solutions are completely dissolved, an electric magnetic mixer is used for 2 hours to mix each solution. To further fully dissolve the solutions, an incubator set at 37° can be optionally used as its slightly higher temperature can make the dissolution easier.

Once both solutions of PLA and chitosan are completely dissolved respectively, *a PLA-Chitosan solution is created* between five different ratios and distributed in 5 test tubes. Each test tube will hold a different ratio of the PLA and chitosan solution: only PLA, 2% Chitosan, 5% Chitosan, 10% Chitosan, and 20% Chitosan. A uniform distribution is desirable as large amounts of aggregation can lead to the formation of microcracks, which can compromise the material's structural performance.

To create the final test products, the contents of each test tube are poured in their respective petri dish. The five petri dishes will be placed into a dryer without air flow at 25° Celsius for 48-72 hours to evaporate the water and leave a thin film. The five resulting thin films are the test products used for the performance test procedures.

2.5 Performance test procedures

Five different performance tests are conducted to determine which ratio between PLA and Chitosan is the most suitable for use as a menstrual pad material. *A surface morphology analysis is conducted first.* Each film is placed under an Optical Microscope (OM) and a Scanning

Electron Microscope (SEM). Machines were adjusted until clear images were exhibited. The detailed images from the machines enable analysis of the surface morphology of the composite material.

To test the mechanical properties of each of the five films, a Universal Testing Machine (UTM) is used. The UTM provides a graph depicting the amount of stress applied to the material and the point where the stress rips the material (usually indicated by a sharp point in the graph). In addition, the machine provides numbers for stress which is key to calculate the Young's Modulus of my material. Below are the equations used to analyze the mechanical properties of the films:

Formula for Elongation at Break: **e = (La - L0) / L0**

e = elongation at break
L0 = initial length of the material
La = length at which the material breaks

Formula for Young's Modulus: **E = σ / ε**

E = measure of the stiffness or elasticity of a material
σ = stress
ε = strain or elongation at break

The water absorption analysis used 2.0 cm squares from each film. These samples are weighed, immersed in water for 24 hours, pat dried, reweighed, and then calculated for the water absorption percentage. Below is the equation used to calculate the water absorption:

<u>Water Absorption (%) = (Absorbed weight – Dry weight) * 100 / Dried weight</u>

When testing for antibacterial properties, two test tubes are each filled with 2.0mL of liquid cultural medium and each holds a different bacterium of either Escherichia coli or *Staphylococcus aureus*. The two test tubes are placed into the automated shaker machine for 30 minutes at 200rpm at 37° Celsius. Once finished shaking, the two test tubes' contents are distributed among 10 other test tubes. Five of the test tubes are filled with 250mL of the cultural medium filled with Escherichia coli and the other five are filled with 250mL of the cultural medium filled with *Staphylococcus aureus*. One sample of each film composite is immersed in a test tube with *E. coli* and another sample of each film composite is immersed in a test tube with S. aureus. The ten test tubes are placed in the automated shaker machine for 30 minutes at 200rpm at 37° Celsius. Afterwards, the ten test tubes are taken out and each test tube's contents are poured into an individual petri dish with a solid cultural medium. Each of the ten test tubes' contents are poured into their respective petri dishes with a solid cultural medium and left in the incubator at 37° Celsius overnight.

$$\text{CFU ml}^{-1} = \frac{\text{CFU per plate} \times \text{dilution factor}}{\text{volume of sample taken (ml)}}$$

Log Reduction = $\log_{10}(A/B)$

A = initial # of microorganisms

B = final # of microorganisms

For the biodegradation test, 3.0 cm square samples are buried in garden soil. The samples are dug up after two, four, and six weeks. Each time the samples are uncovered from the ground, they are cleaned, photographed, and weighed to track the degradation. The mass percentage to its original mass will be calculated for each composite along with their mass loss rate.

3. RESEARCH RESULTS AND DISCUSSIONS

3.1 Analysis of Surface Morphology of Composites

The dispersion of the chitosan within the PLA matrix is crucial in creating a suitable material for menstrual pads. The more uniform the dispersion of the chitosan is, the more likely favorable properties are exhibited, and the less likely aggregation is present. This uniformity heavily relies on the ratio between chitosan and PLA in the composite and can be examined under the OM (Figure 2) and SEM (Figure 3). In both Figures, the circular domains in each image represent the chitosan particles while the rest is PLA. It is evident that as the ratio of Chitosan to PLA increases, the number of circular domains increases.

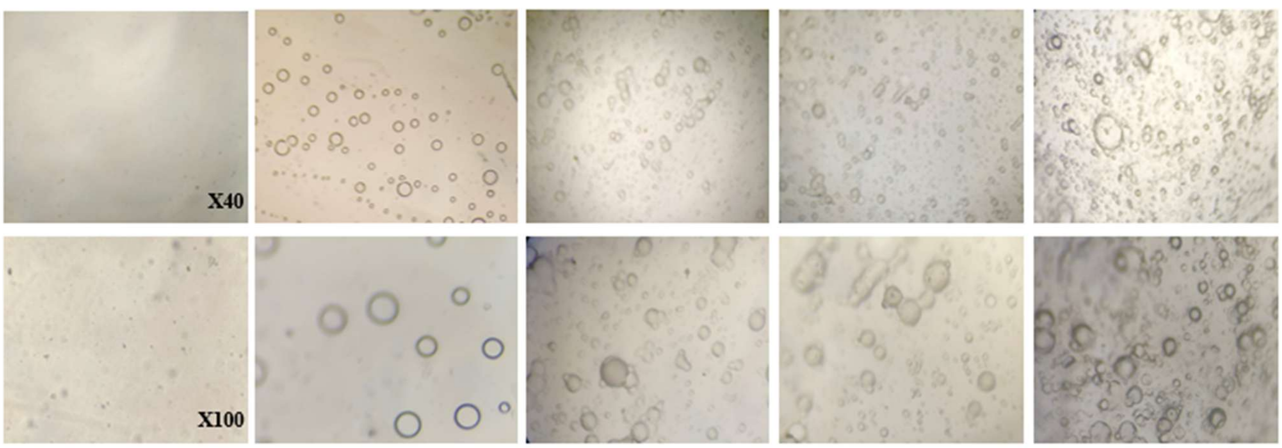

Figure 2. Solvent film formation under optical microscope (From left to right PLA, PLA/2% CS, PLA/5% CS, PLA/10% CS and PLA/20% CS) first emission is 40 times larger, and the second emission is 100 times larger

However, in Figure 3, the difference between PLA/10% CS and PLA/20% CS is drastic as the circular domains become profoundly enlarged in PLA/20% CS. When the percentage of chitosan becomes too significant, in this case PLA/20% CS, the chitosan particles clump together and aggregate while causing phase separation. Clumps are troublesome as this leaves areas in the composite without chitosan. These lacking regions will not have the necessary properties of Chitosan to support the composite's purpose while lessening its performance capabilities. This reduction is evident throughout the entire performance test analysis.

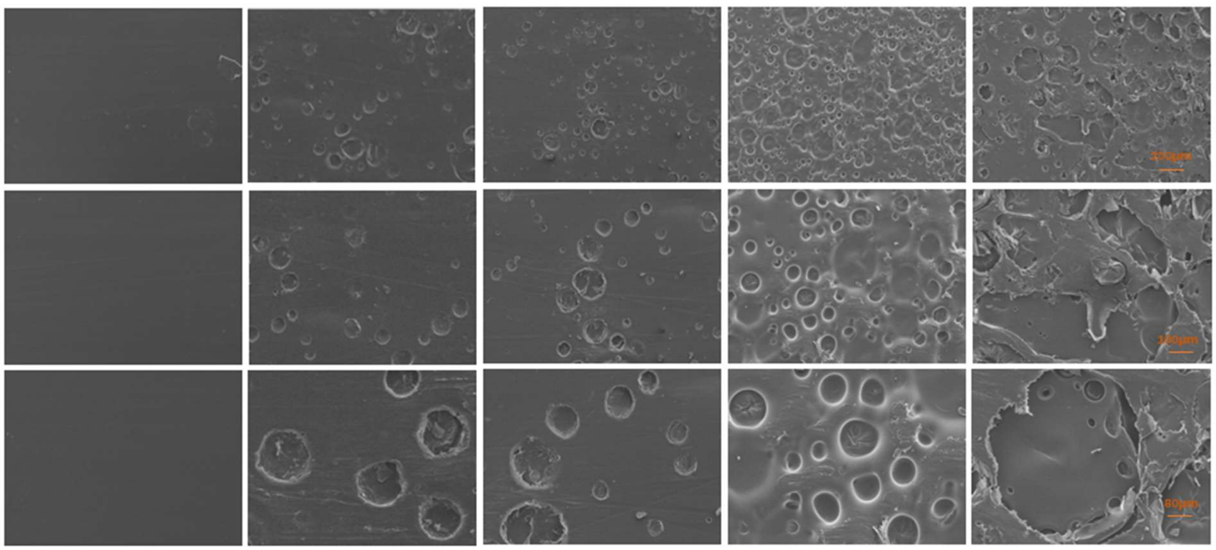

Figure 3. Solvent film formation under SEM (left to right PLA, PLA/2% CS, PLA/5% CS, PLA/10% CS and PLA/20% CS)

3.2 Effect of Chitosan on Composites' Mechanical Properties

The mechanical properties of the composite are determined using a UTM and calculating the elongation at break and Young's Modulus. To create a material favorable for menstrual pads, it must be able to undergo high stress, have high elongation at break, and a low Young's Modulus. Thus, the menstrual pad will not easily break or tear, even after a long day's use. According to Figure 4 and Table 1, the ratio of PLA/10% CS is most favorable. This is supported in Table 1 as PLA/10% CS displays a stress of 45.5 MPa and a strain of 7.1%, the highest among all the PLA-Chitosan composites.

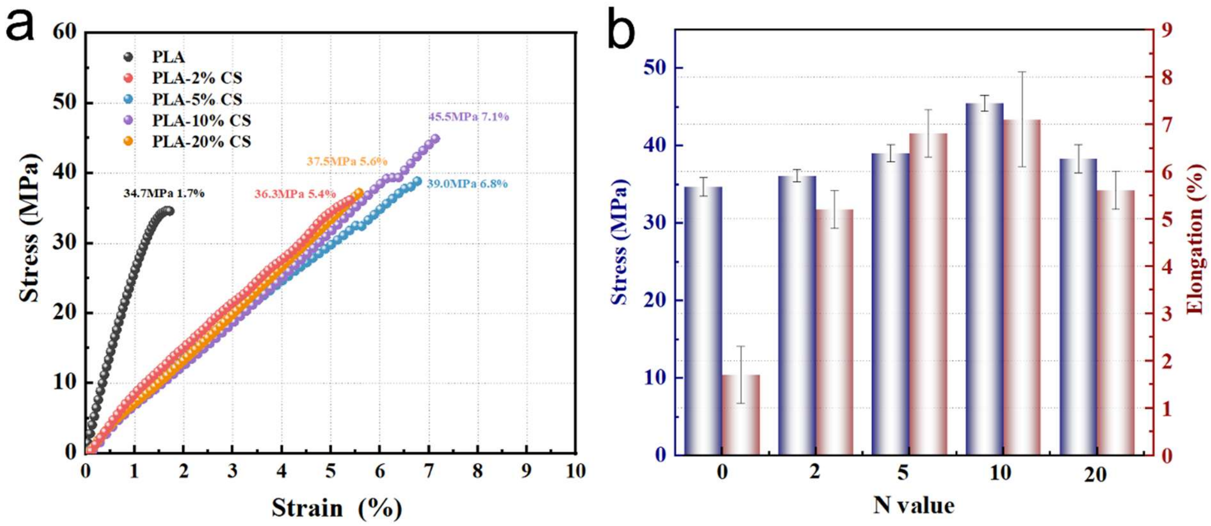

Figure 4. Stress−strain curves of PLA, PLA/CS and maximum strength, elongation at break, toughness values

Table 1. Breaking Strength, Elongation at Break, Toughness Values of Various Composites

Samples	Tensile strength (MPa)	Elongation at break (%)	Toughness (MJ/m3)
PLA	34.7±1.2	1.7±0.6	0.4±0.05
PLA/2% CS	36.3±0.8	5.4±0.4	1.1±0.1
PLA/5% CS	39.0±1.1	6.8±0.5	1.4±0.1
PLA/10% CS	45.5±1.0	7.1±1.0	1.6±0.2
PLA/20% CS	37.5±0.8	5.6±0.4	1.0±0.1

PLA/10% CS is the optimal concentration in creating a suitable material because the stress concentration is most continuous throughout this composite. Chitosan is crucial in creating a flexible material, because it can address PLA's rigidity and increase the material's elasticity.

More chitosan makes the material more flexible because it is the area where stress is applied to the most. However, a uniform composition between PLA and chitosan is also critical in creating a high-quality material for menstrual pads. Too much chitosan can cause aggregation and phase separation, resulting in only specific areas of the material to retain its flexibility while other areas without chitosan will easily fracture due to PLA's rigidity. This can be visualized through stress concentration, or concentration of stress-flow lines within the material. Because chitosan is soft, the concentration of stress starts there and then continuously spreads to PLA. However, when too much chitosan is concentrated in one area, the stress concentration focuses on one area and ultimately breaks the material. Griffith's theory of fracture supports this (Hoek & Bieniawski, 1984). All real materials have flaws, microcracks or other defects. Small flaws in the material require high stress to break while larger flaws need less stress. Thus, to reduce the amount of stress applied to the small flaws in the material, it must be dispersed throughout the material, distributing the stress more evenly. By ensuring an even distribution of chitosan within the PLA matrix, the material can avoid regions with excessive stress concentration and discourage fractures. This highlights the importance of optimizing the ratio between PLA and chitosan to achieve a homogeneous mixture.

3.3 Water Absorption Properties of Composite

Water absorption percentage is an important characteristic of menstrual pad materials. High water absorption indicates that the material can take in a large volume of blood before it starts leaking. If a material has low water absorption traits, it will easily leak period blood making it unattractive for menstrual products. Figure 5 portrays PLA/20% CS has the highest water absorption percentage at 25.3 water absorption percentage. This is due to its high concentration of chitosan. PLA is hydrophobic, which is why it only had a 1.2% water absorption percentage. Meanwhile, chitosan is hydrophilic which is why as the ratio of PLA to chitosan increases, the water absorption property increases as well. Chitosan's hydrophilic properties are not only extremely important for the purpose of absorbing blood, it also provides the foundation for its ability to attract microorganisms.

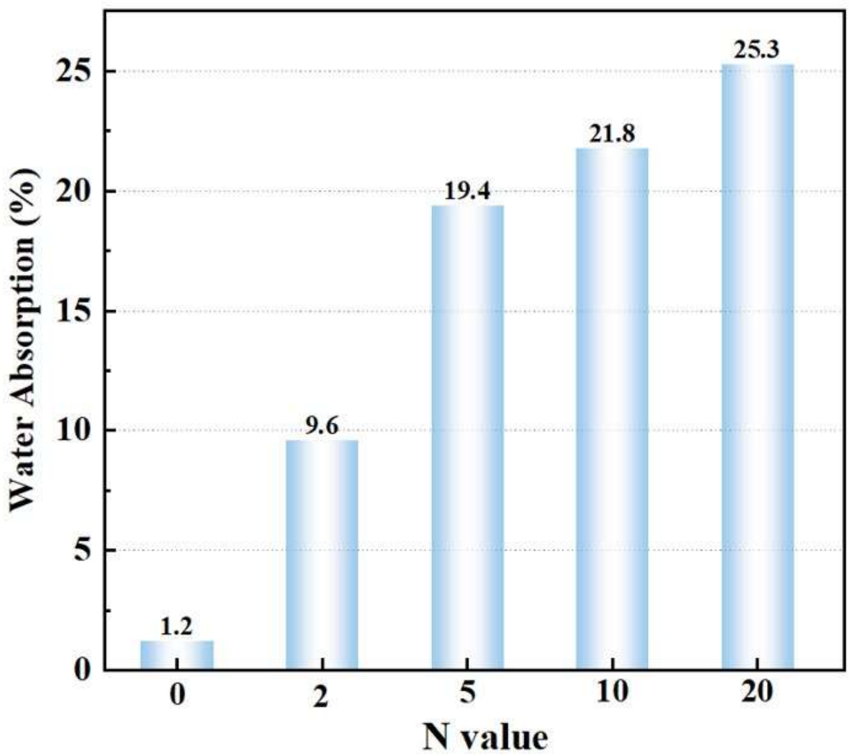

Figure 5. Water Absorption Percentage between PLA-Chitosan Composites

3.4 Effect of Chitosan Concentration on Composites' Antimicrobial Activity

Chitosan concentration holds significant control over the composites' microbial activity. The microbial activity in the research experiment is tested in terms of the composites' antimicrobial properties and biodegradation properties. For antimicrobial activity, Figure 6 visually portrays the comparison of bacterial presence between the PLA-chitosan composites. In the first column with just PLA, the petri dishes are filled with bacteria, indicated by the large amount of tiny white dots that crowd the petri dishes. In the last column with PLA/20% CS, there are only several white dots in the middle of the petri dish. Qualitatively, it can be seen PLA/20% CS has a significant decrease in number of bacterial colonies in comparison to just PLA. Quantitatively, Table 2 demonstrates that PLA/20% CS had the smallest colony forming units (CFU), 2.92×10^9 for *E. coli* and 4.54×10^9 for *S. aureus*, meaning it had lowest amount of bacteria colonies compared to the rest of the composites with lower chitosan concentrations. In addition, PLA/20% CS's log reduction was the greatest among the composites, meaning its reduction in bacteria colonies was the most significant. This is due to it having the greatest chitosan concentration.

Table 2. Colony Forming units and Log Reduction of *Escherichia coli* and *Staphylococcus aureus*

Ratio	**CFU/mL**		**Log Reduction**	
	E.coli	*S.aureus*	*E.coli*	*S.aureus*
Control	4.17×10^{11}	3.81×10^{11}	-	-
2	3.61×10^{11}	2.12×10^{11}	0.06 ± 0.13	0.25 ± 0.28
5	7.85×10^{10}	4.23×10^{10}	0.71 ± 0.14	0.92 ± 0.59
10	3.49×10^{10}	1.14×10^{10}	1.05 ± 0.51	1.53 ± 0.27
20	2.92×10^{9}	4.54×10^{9}	2.13 ± 0.38	1.92 ± 0.13

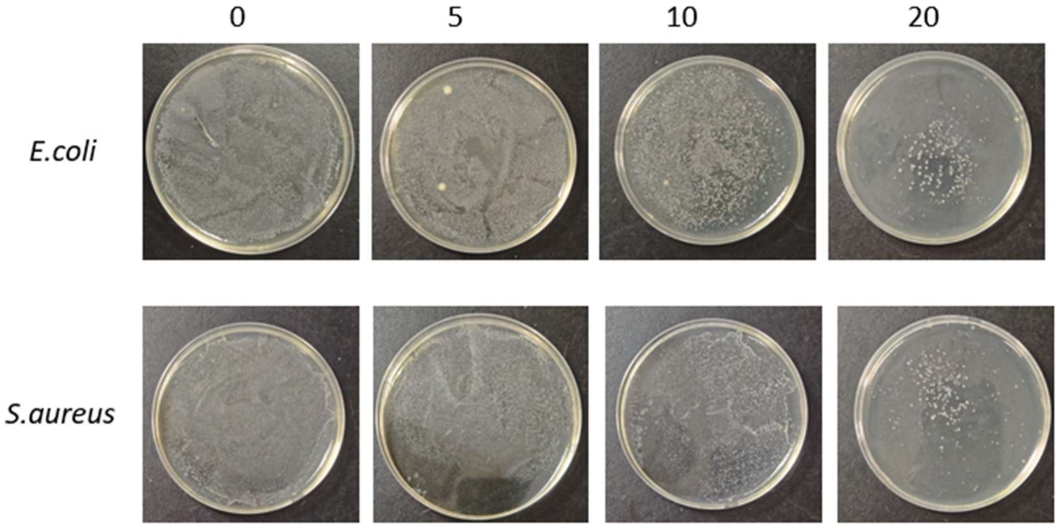

Figure 6. Images of Petri Dishes with Bacteria and Composite Films (left to right PLA, PLA/5% CS, PLA/10% CS and PLA/20% CS)

Chitosan is responsible for the composites' antimicrobial activity. While there is evidence that chitosan's antimicrobial properties rely on several factors, it is certain that it relies on its protonation degree. The reason is because most bacterial cells have a negatively charged cell wall. Chitosan can only bind itself and disrupt the bacterial cell wall if it is attracted to the negative charge, meaning it must have a positive charge. Once attracted, chitosan could create a hole in the bacteria cell's membrane, allowing cytoplasmic materials to be lost. Chitosan could also enter the cell and end the bacteria's protein and mRNA synthesis (Sahariah, 2017). To maintain a positive charge, one can look to chitosan's degree of acetylation. A lesser degree of acetylation is preferrable for chitosan as it indicates that there is less neutralization of the chitosan's positive charge. Moreover, less acetylation implies a greater amount of free amino groups to interfere with the bacterial cell. Protonation degree also depends on the cultural medium's pH level. Chitosan is seen to show enhanced antibacterial performance under environments where the pH of the cultural medium is lower than the pKa level of the chitosan (Sahariah, 2017). In addition, our results showed chitosan's effectiveness against both bacterial types, with slightly higher inhibition against *E. coli* (gram-negative) compared to *S. aureus* (gram-positive), consistent with chitosan's charge-based antimicrobial mechanism. Therefore, our experimental procedure is highly favorable as it dissolved chitosan in acetic acid, improving the polymer's antibacterial properties.

3.5 Effect of Chitosan Concentration on Composites' Biodegradation Behavior

However, chitosan does not inhibit all microbial activity. Chitosan is biodegradable, which means that microorganisms are attracted to the polymer to break it down into smaller components. Figure 7 qualitatively depicts this: as the chitosan concentration in the composites increased, the material's biodegradability increased. In week 6 for solely PLA, the material barely decayed into smaller pieces. Meanwhile, week 6 for PLA/20% CS exhibited an increase in biodegradable properties as it portrays smaller fragments of the original material. Additionally, brown coloring appears on the sample, indicating the development of a biofilm, which is beneficial for biodegradation. The reason why a biofilm only develops with PLA/20% CS is because these microorganisms are attracted to humid environments and this composite retains the most water compared to the rest. This is because the greater amount of chitosan, the more hydrophilic the material is which increases the material' attraction to absorb water. While PLA is biodegradable, the addition of chitosan greatly enhances this property, highlighting the importance of this additive.

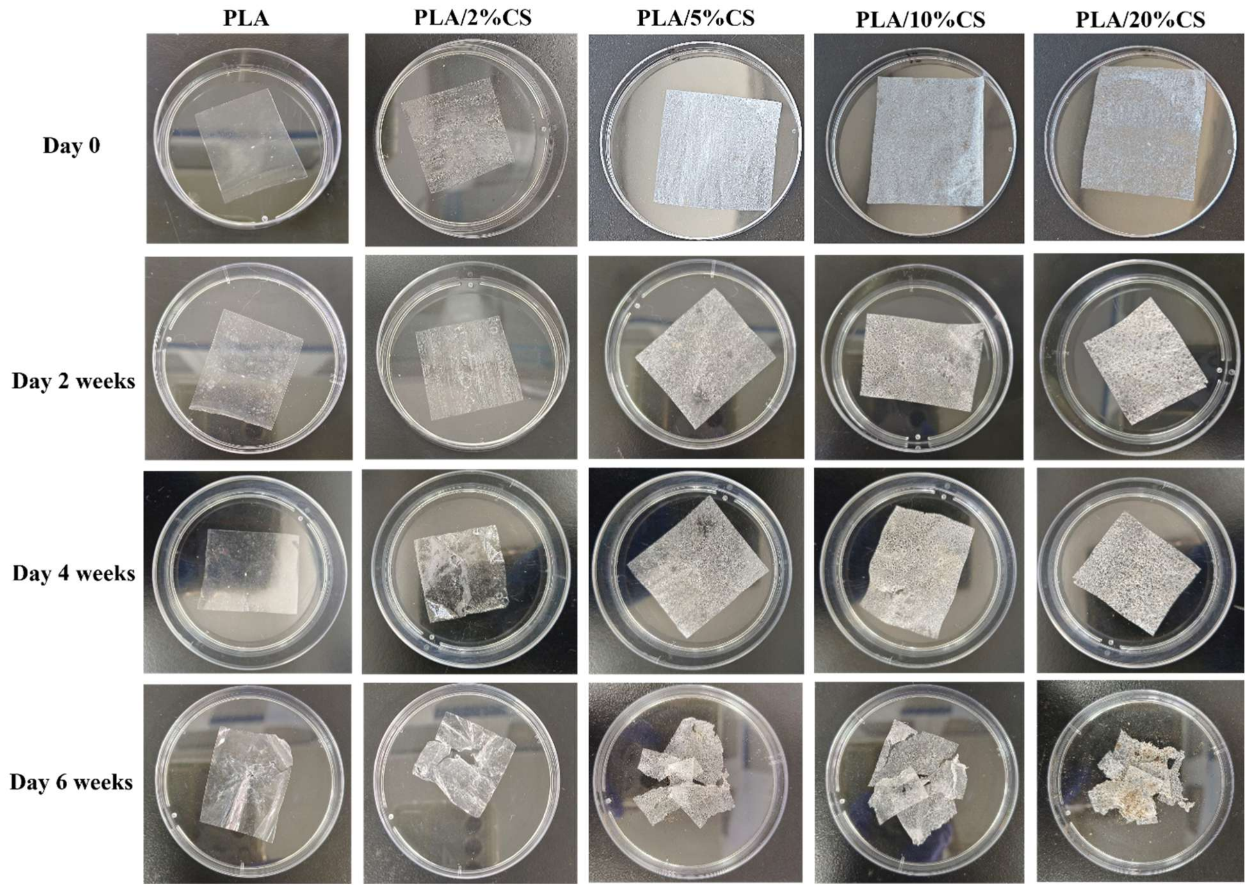

Figure 7. Biodegradation of PLA-Chitosan Composites over 6 weeks with 2-week Intervals

Figure 8 supports this. At 4 weeks, PLA/10% CS exhibited cracks along the material, as indicated by the arrows. Meanwhile, PLA/20% CS demonstrates large holes underscoring the how the difference in chitosan can affect its degradation rate. Overall, with greater chitosan concentration, the bubbles increase in increase, demonstrating the significance in the how the amount of chitosan can affect the material's biodegradation properties.

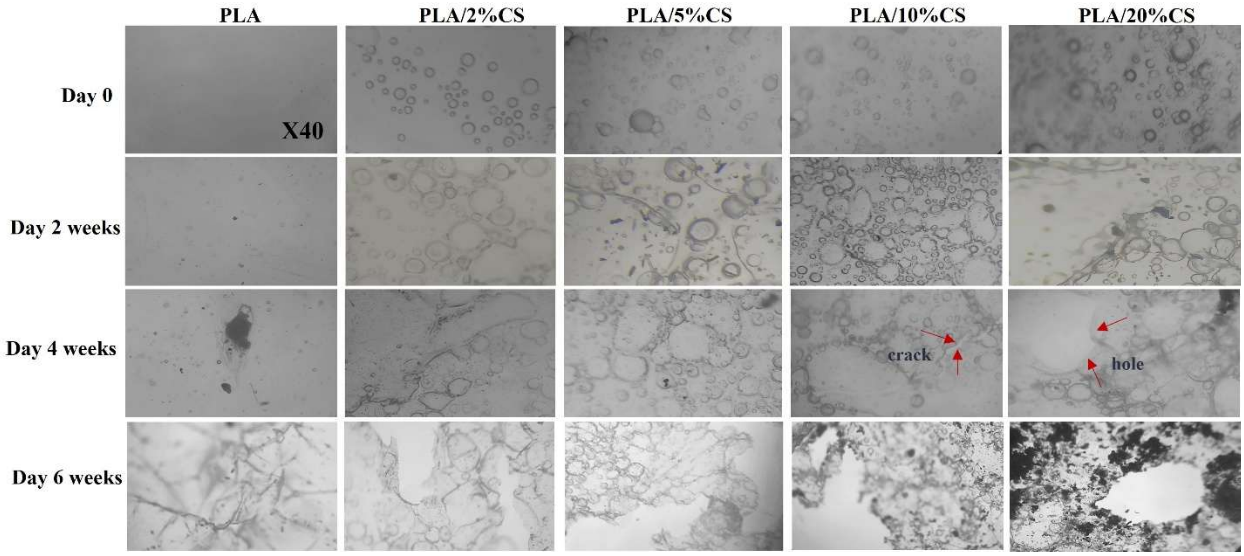

Figure 8. OM Images of Biodegradation of PLA-Chitosan Composites over 6 weeks with 2-week Intervals

Quantitatively, Figure 9a demonstrates for every 2-week interval, PLA/20% CS had a lower mass percentage compared to the rest of the composites. Table 3 states it had the lowest mass at the end of the 6 weeks with a 39.1% mass percentage. Moreover, 9b highlights for every interval, PLA/20% CS had the highest mass loss rate percentage. This means the microorganisms were more attracted to this film and broke down the components quicker.

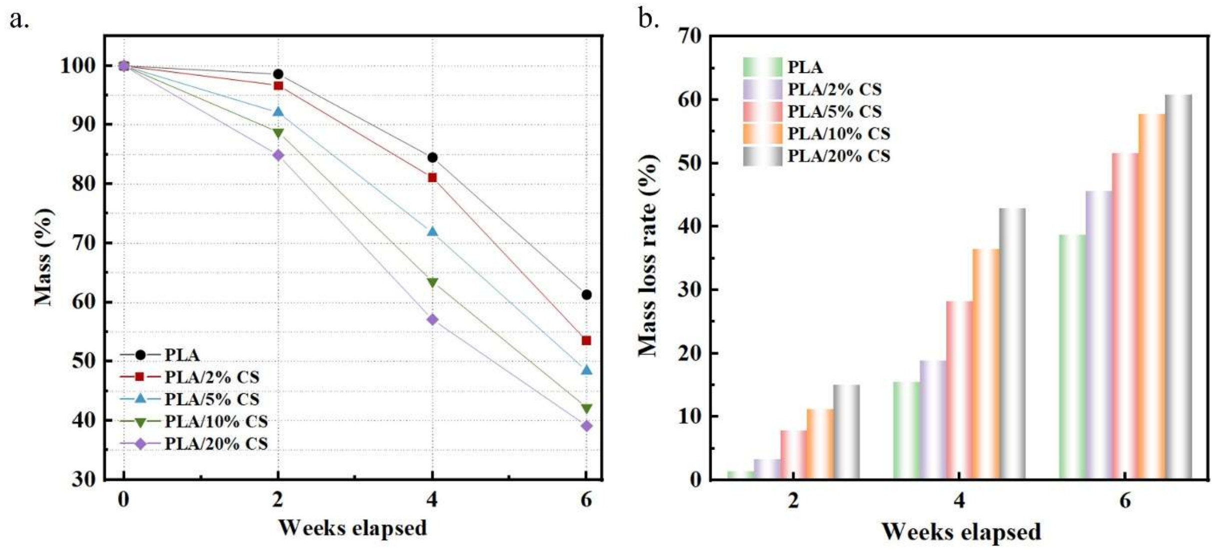

Figure 9. Analysis of PLA-Chitosan Composites' Biodegradation Properties (**a**. Weeks Elapsed to Mass percentage of Initial Mass **b**. Weeks Elapsed to Mass Loss Rate Percentage)

Table 3. Mass Percentage of PLA-Composites over 6 weeks in two-week intervals

Mass	0 weeks	2 weeks	4 weeks	6 weeks
PLA	100%	98.6%	84.5%	61.3%
PLA/2% CS	100%	96.7%	81.1%	53.5%
PLA/5% CS	100%	92.1%	71.8%	48.4%
PLA/10% CS	100%	88.8%	63.5%	42.2%
PLA/20% CS	100%	84.9%	57.1%	39.1%

This raises the question: "How can chitosan be both antibacterial and biodegradable?" Two reasons can explain this. One reason is that chitosan is selective in its behavior towards the type of bacteria. It repels what it considers "harmful" bacteria and attracts bacteria necessary for biodegradation. In the research experiment, as the chitosan concentration increased, fewer colonies of the “harmful” bacteria were *E. coli* and *S. aureus* remained. Meanwhile, those “harmful” bacteria do not degrade chitosan. Other microorganisms cause biodegradation and were rather more attracted to the materials as more chitosan was found in the material. This analysis implies the chitosan only attracts microorganisms necessary for biodegradation. The second reason is that chitosan’s behavior to bacteria is time dependent. The antimicrobial experiment was done in a time period of 24 hours while the biodegradation test was conducted over 6 weeks. This suggests that chitosan’s antimicrobial properties may dominate for a short period of time but will eventually be overpowered by its biodegradable properties as time progresses. This dual functionality of chitosan makes chitosan ideal for menstrual products. These products are used for only a few hours before disposal meaning its antimicrobial properties will shine during product use while its biodegradability properties will grow to be more effective after the product’s use.

CONCLUSION

Based off the research, the composite with PLA/10% CS and PLA/20% CS proved most optimal results for the purpose of menstrual pad material. PLA/10% CS was the most effective in mechanical properties as it demonstrated the highest tensile strength, elongation at break, and toughness. Meanwhile, PLA/20% exhibited the highest performance in water absorption properties, antimicrobial properties, and biodegradation properties. This is due to it having the highest concentration of chitosan in which chitosan is the main factor in how prominent these three properties are.

To enhance the outcomes of this research, future work should focus on optimizing the blending procedure to achieve a more precise concentration between 10% and 20% chitosan, aiming for the best balance of mechanical strength and functional properties. To achieve this, adopting alternative processing methods such as PLA emulsification or Pickering emulsification could improve the dispersion of PLA and chitosan. Moreover, unlike organic solvents used in the current study, these techniques utilize water as a solvent, making them more environmentally sustainable.

This composite's versatility and unique properties open the door for medical applications, including wound dressings, surgical sutures, and antimicrobial packaging, where biocompatible and antimicrobial properties are needed. Its ability to combine strength, antimicrobial protection, and eco-friendliness positions it as a promising material for advancing sustainable healthcare products. Lastly, this composite can also be applied to other forms of absorbent hygiene products such as postpartum pads, diapers, and incontinence pads.

The dual functionality of chitosan, combining both antibacterial and biodegradable properties, makes it particularly ideal for menstrual products. Chitosan repels harmful bacteria while attracting the microorganisms necessary for biodegradation, with its antibacterial effects dominating initially and its biodegradability becoming more effective over time. This characteristic perfectly aligns with the needs of menstrual pads, which require antimicrobial safety during use and environmental breakdown after disposal. Ultimately, the balance of performance, safety, and sustainability demonstrated by the PLA/chitosan composite highlights its potential as a superior choice for menstrual pad materials and other medical applications.

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