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Biodegradable Self-Healing Textiles with Integrated Chemical Neutralization for Sustainable Protective Applications

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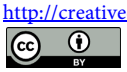


Abstract

The development of biodegradable self-healing textiles presents a potential solution for sustainable protective applications in response to rising environmental concerns. Research presents an innovative method for creating environmentally friendly fabrics that have integrated chemical neutralization and self-healing properties. The fabric is treated with a biodegradable polymer matrix incorporating phytic acid (PA) and $CaCO_3$ ($CaCO_3$) for enhanced flame resistance and self-healing properties. The chemical composition of the cloth helps neutralize acidic conditions after mechanical damage, thereby healing structural damage. The creation of a protective $CaCO_3$ layer that seals crack and restores the fabric's integrity is how the self-healing process works. Furthermore, the addition of PA catalyzes the dehydration of cellulose, enhancing the fabric's resilience to flame and thermal stability. The treated fabrics provide superior flame resistance, and even after several washing cycles, they continue to exhibit their self-healing properties. Research demonstrates the possibility of integrating chemical neutralization, self-healing processes, and biodegradable materials to produce safe, sustainable textiles for a range of industrial uses.

Keywords

Biodegradable, Self-Healing Textiles, Chemical Neutralization, Phytic Acid (PA), Calcium Carbonate ($CaCO_3$)

1. Introduction

Self-healing biodegradable fabric is a breakthrough in the production of innovative fabrics that are environmentally friendly. These fabrics are developed to fit

this emerging need for green products as well as improve on the protective features [1]. Built-in features of self-repairing textiles provide the fabrics with the ability to heal themselves and this eliminates the need for replacing the fabric most of the time. This aspect is especially desirable in protective applications where the structural characteristics of the fabric play a significant role [2]. Although textile engineering has come a long way, traditional protection fabrics still have significant drawbacks. Limitations in reusability, loss of mechanical integrity with repeated exposure to mechanical, thermal, or chemical stress, and lacking an autonomous damage recovery mechanism are prevalent issues for traditional protection fabrics. Their disposal at end-of-life often leaves a lasting consequence concerning environmental pollution because the use of synthetic polymers cannot degrade. All of these drawbacks can negatively affect the functional, environmental, and financial value of any traditional protection fabric. To satisfy the growing global demand for high-performance and sustainable textile applications, it is required that the current limitations are overcome. To address the worldwide demand for high-performance, eco-friendly solutions in different sectors, particularly in protective textiles, sustainable materials must be created. This revolutionary invention brings together environmental stewardship and advanced practical capabilities of self-healing fabrics [3]. Because the textiles are made to repair themselves from minor damage, clothes endure longer and produce less waste [4]. **Figure 1** shows the biodegradable self-healing textile process.

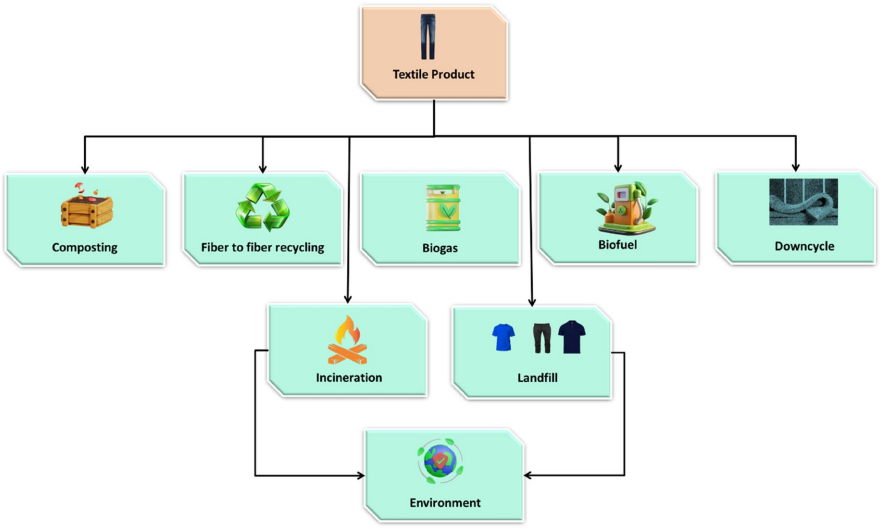


Figure 1. Process of biodegradable self-healing textiles.

Moreover, better resistance to hazardous substances through the use of chemical neutralization ability and thus are well-suited for industrial, defense, as well as health industry applications [5]. Together with increased durability and security of protective gear, the combination of chemical neutralization with self-healing also promotes sustainability by reducing impact on the environment [6]. Biodegradable materials ensure that at the end of their cycle, these textiles break down

naturally with no harmful leftovers, which will favor efforts to diminish plastic waste in many parts of the world and lead to a circular economy [7]. This multidisciplinary approach utilizes new developments in material science, nanotechnology, and green chemistry, promising an exciting road for the future of smart, eco-friendly protective textiles [8]. The biodegradable self-healing textiles are optimized with improved flame resistance properties by incorporating phytic acid (PA) and calcium carbonate ($CaCO_3$) in a polymer matrix. The objective of this approach is to achieve sustainable and durable fabrics for protective uses with compatibility with the environment.

The present research is divided into five phases. Phase II presents the related works, the research methodology is explained in Phase III, Phase IV illustrates the result and discussion; and finally, the conclusion is described in Phase V.

2. Related Works

The development of multipurpose and customized surfaces for cotton fibers that can be securely incorporated into fabrics that provide products' versatility and enhance their usefulness has become the primary objective of cotton research recently. The straightforward synthesis method [9] offered a practical way to produce multipurpose, recharged antimicrobial fabrics in large quantities, which could potentially be used in healthcare equipment and household sanitation items. To reduce burn damage to individuals in fire accidents [10], it was essential to construct permeable fabric with piezoresistive sensor capacities and ultrasensitive fire alarm responsiveness. Additional information was offered on the development and use of multipurpose fabric sensors. The limited endurance of monolithic functional textiles was addressed by using a multifunctional waterborne polyurethane nanodroplet containing disulfide bonds (WSPU). The WSPU nanodroplet coating [11] enabled textiles' directional transportation, self-treatment at ambient temperature, hydrophobicity, and antimicrobial capabilities. With the combined impact of multiple functionalities, this research provided a chance to investigate the creation of multipurpose textiles. The damaged Organic Light-Emitting Devices (OLEDs) could regain their lowered brightness [12], and the structural variation brought by the OLEDs' repeated movements can be returned to their original form. Additionally, the recently created self-healing OLEDs, which can self-heal after harm, represent an entirely novel innovation in smart clothing systems.

According to the research [13], the cohesiveness of the biofilm and the adherence of the biofilm to the textile were both necessary for the durability of self-repairs. Given that fibers could be genetically manipulated, the creation of self-repairing curli-expressing biofilm-textile combinations brought up new possibilities for the commercial production of affordable, durable, and eco-friendly multipurpose apparel. To produce sustainable superhydrophobic filters [14], myristic acid would be applied to cotton fabric after silica particles have been adsorbed. Oil-water solutions comprising dichloroethane, hexane, toluene, xylene, or chloroform were passed through a superhydrophobic cotton filter. In addition to

achieving separation efficiency, the filter showed outstanding chemical resistance, self-healing capabilities, resilience, and reuse. Carbon Nanotubes (CNTs) and Biodegradable Polyurethane (BTPU) were used to produce a flexible sensor covered in cotton fabric. Additionally, the cloth demonstrated biological properties with the human skin, which qualifies it for use with wearable skin-contact sensors. Research [15] provided information for the creation of high-performing, biodegradable sensors for electronic skins and wellness monitoring equipment. Hydrogel adhesives were developed using catechol-conjugated gelatin derived from the environment, ferrous ions, and synthesized polymers [16]. These hydrogel adhesives' numerous benefits, such as enhanced tissue adhesion, degradability, self-treatment, cytocompatibility, and antimicrobial properties, make them highly intriguing for application as tissue adhesives in the medical field. Despite the wearable potential of Hydrogen (pH) sensors having applications for ecological identification and medical tracking, their endurance was a concern because of possible harm. Wearable pH sensors would benefit from the significant approach [17] for creating long-lasting, pH-responsive coated textiles with self-treatment and recycled properties.

3. Methodology

The methodology involves treating the fabric with a biodegradable polymer matrix infused with PA and $CaCO_3$ to enhance flame resistance and enable self-healing. The process leverages the chemical neutralization of acidic conditions and the formation of a protective $CaCO_3$ layer to repair structural damage and maintain fabric integrity. Figure 2 shows the process of the suggested method.

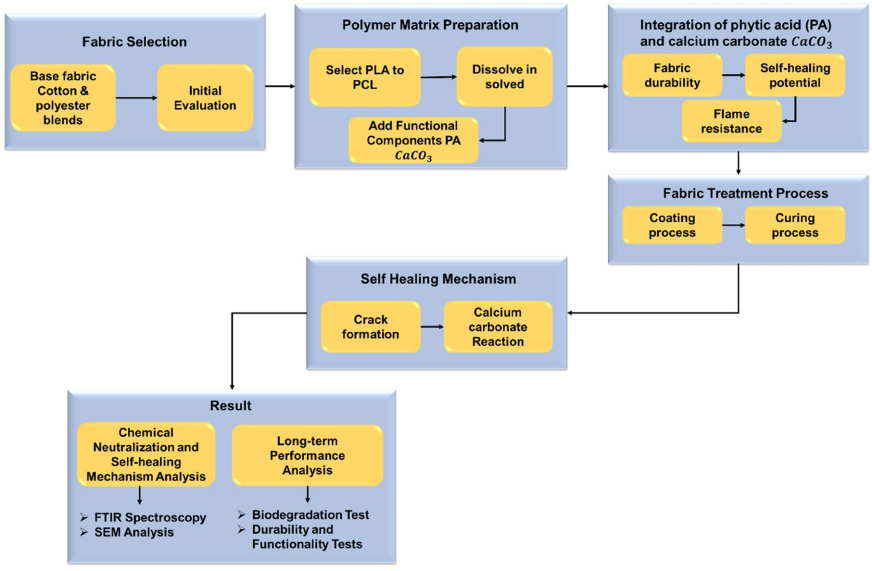


Figure 2. Process of proposed methodology.

3.1. Fabric Selection

The cotton fabric data (COT, 160 g/m^2) and polyester fabric data (POL, 120 g/m^2)

were obtained from the industries. The choice of using cotton and polyester blends was informed by its cardinality in most protective apparel; the features include comfort, breathability, moisture absorption, and the addition of polyester, which offers superior strength, durability, and wrinkle resistance. The types of fibers used in this textile were chosen to consider compatibility for treatment with fire-resistant and self-healing properties inherent in industry and real-world practices.

3.2. Polymer Matrix Preparation

The preparation of the polymer matrix starts with the selection of a biodegradable polymer. The polymer selected can be poly (lactic acid) (PLA) or polycaprolactone (PCL). PLA is selected due to its biodegradability, non-toxicity, and wide use in sustainable applications. On the contrary, PCL is chosen for tremendous flexibility and slower degradation, which makes it suitable for long-term applications. In an appropriate solvent system, such as acetone or chloroform, the selected polymer dissolves to create a uniform polymer solution. A full solution takes about thirty minutes under normal conditions. The textile receives an application of the prepared solution. The solution can receive either COT, 160 g/m^2, or POL, 120 g/m^2 based on particular application requirements. The solution breaks down polymers into microparticles through solvent action, which enables consistent particle distribution throughout the solution until a uniform fabric coating forms. To control the coating performance, the concentration of the polymer solution should be adjusted according to the viscosity. This process of adjusting viscosity normally can take approximately 20 minutes. The ensuing polymer solution can be blended with other components such as PA and $CaCO_3$, which are introduced in the fabric matrix in order to improve its flame retardancy and self-healing characteristics. A time of approximately 90 minutes is consumed during final preparation, which comprises the application and the curing steps to produce a strong and protective fabric to achieve different routines.

3.3. Integration of Phytic Acid (PA) and Calcium Carbonate ($CaCO_3$) for Improving Flame Resistance and Self-Healing Properties

When combined, PA and $CaCO_3$ improve the fabric's durability, self-healing potential, and flame resistance, which qualifies it for environmentally friendly, protective textile applications.

3.3.1. PA Addition for Flame Resistance

The polymer matrix is introduced to a specific concentration of phosphorus-rich natural organic phytic acid (PA, $C_6H_{18}O_{12}P_6$). PA is an important contributing component to the flame resistance of the fabric. It acts catalytically in the process of dehydration of cellulose fibers ($C_6H_{10}O_5$) in the fabric, forming better layers of char during burning. These char layers offer resistance and delay the flares of ignition and spread of flames. More importantly, PA helps in stabilizing the polymer structure itself so that the overall thermal stability of the fabric would further

be improved. The dehydration of cellulose fibers can be represented by the following Equation (1).

$$Cellulose\left(C_6H_{10}O_5\right) \xrightarrow{PA} Char + Water\left(H_2O\right) \quad (1)$$

This reaction shows the catalysis of cellulose ($C_6H_{10}O_5$) breakdown into char, which enhances flame resistance. The time required for the formation of char through the dehydration process catalyzed by PA is roughly 5 min - 10 min at temperatures between 250˚C - 300˚C. This enables the reaction to proceed sufficiently for the formation of char and its stabilization.

3.3.2. $CaCO_3$ Addition for Self-Healing and Flame Resistance

$CaCO_3$ is added to the polymer matrix, which not only improved its flame retardation but also helped self-heal. If the fabric (such as COT, 160 g/m^2, POL, 120 g/m^2) containing $CaCO_3$ encounters a heat or flame attack, then its thermal decomposition generates CO_2 along with leaving a calcium oxide (CaO). These oxides interact with environmental moisture, covering it with an additional protective layer of $CaCO_3$ over the textile. This layer seals the cracks and damages caused by mechanical stress, thus effectively restoring the integrity of the fabric. Such a self-healing process not only repair minor physical damages but also enhances the durability of the fabric over time. The presence of $CaCO_3$ improves the overall flame resistance of the fabric by promoting the formation of stable, heat-resistant layers during combustion. The decomposition of $CaCO_3$ and its interaction with moisture can be represented by the following Equations (2 and 3).

Thermal Decomposition: The decomposition of $CaCO_3$ under heat normally lasts for 2 - 5 minutes at temperatures between 600˚C and 800˚C.

$$CaCO_3 \xrightarrow{Heat} CaO + CO_2 \quad (2)$$

Reaction with Moisture to form $CaCO_3$: The regeneration of $CaCO_3$ coating and moisture interaction for appliance self-healing can take between 30 minutes and 1 hour, depending on the external conditions.

$$CaO + H_2O \xrightarrow{Moisture} CaCO_3 \quad (3)$$

These reactions show the decomposition of $CaCO_3$ under heat and its interaction with moisture to regenerate $CaCO_3$, forming a new protective layer that enhances both self-healing and flame resistance.

3.4. Fabric Treatment Process

The two main approaches of the treatment process on the fabrics are dip-coating and spray-coating the base fabrics, cotton (COT, 160 g/m^2) and polyester (POL, 120 g/m^2), in a polymer matrix of 2 wt% phytic acid (PA) and 3 wt% $CaCO_3$. The concentrations of phytic acid and $CaCO_3$ were determined from optimization in that they led to suitable levels of flame retardancy and self-healing. Also, after coating, the fabric is cured afterward to ensure proper adhesion of the matrix and crosslink.

Dip-coating and spray-coating procedures: the fabric is fully submerged in the polymer mixture for a period of 10 minutes to ensure that a uniform and consistent layer covers the surface. After the immersion step, the fabric samples were air-dried for 30 minutes at room temperature to allow some initial solvent evaporation. In spray-coating, the same solution was sprayed in a controlled way over the fabric surface using a nozzle at a pressure of 2 bar - 3 bar, at a distance of 15 cm - 20 cm, ensuring a total coverage over the complex fiber structure. The duration of the spray step was 2 min - 3 min per sample, which would then be followed by the same air-dried step.

Curing: Following drying, the coated fabrics will undergo heat curing at 130˚C for 25 minutes, which is the chosen treatment that governs the complete evaporation of all solvents and the resultant bonding of the polymer matrix to the surface of the textile. The conditions achieved during curing, namely temperature and time, are controlled to ensure that thermal degradation of the fabric does not occur while cross-linking of the components of the matrix takes place successfully.

Characterization of Fabric Properties: The performance of COT and POL fabrics after treatment was examined using standard test methods:

1) Flame resistance testing took 15 - 30 minutes with flame ignition delay and flame propagation being measured.

2) Tensile strength testing (30 - 60 minutes) was used to measure mechanical durability after treatment.

3) Self-healing performance was evaluated by making controlled cuts in the treated fabrics and then letting the samples recover for 24 hours in ambient conditions.

4) Washing resistance was measured over 3 - 5 hours with five washing cycles at 40˚C with post-wash flame-retardancy assessment and self-healing assessment.

The results confirm that the treated fabrics are relevant to protective, durable, and sustainable textile applications.

3.5. Study Analysis

The treated fabric possesses high chemical neutralization capacity and self-healing characteristics, which confirms the effectiveness of the incorporation of PA and $CaCO_3$ into the polymer matrix. Analyzing the chemical behavior of the fabric using Fourier Transform Infrared (FTIR) spectroscopy and Scanning Electron Microscopy (SEM) confirms the flame resistance and self-healing properties of the material when it is damaged. The self-healing efficiency is tested over a particular time duration, and biodegradation mainly orients towards the environmental suitability of the fabric. Also, the durability tests enable the determination of the loss of functional properties of the fabric through wear and environmental factors, thus identifying fabrics suitable for long-term protective uses.

4. Result

From the chemical neutralization, the analysis of the self-healing mechanism, and

the long-term performance tests, this evaluation shows that the treated fabric retains its functional properties at an acceptable level during a material's lifespan. The following tests reveal high flame resistance, self-healing potential, and biodegradability properties of the fabric; in addition, the durability of the fabric exposed to environmental stress throughout the test period is not compromised.

4.1. Chemical Neutralization and Self-Healing Mechanism Analysis

The chemical neutralization and self-healing capabilities of treated fabrics are integral for their performance in protective applications. This research employs complex methods such as chemical neutralization and self-healing properties that are crucial for the fabric in protective solutions. An innovative method used in this analysis is FTIR spectroscopy as well as SEM, to determine the interaction of the polymer matrix, PA, $CaCO_3$, and the fabric itself.

4.1.1. FTIR Spectroscopy

FTIR spectroscopy is a useful tool to identify the type of bonds and chemical interactions that exist within the material. It gives the sample spectrum that shows functional groups and how they interact with one another. In this case, FTIR is used to determine the chemical interactions between the PA, $CaCO_3$, and the polymer matrix in the treated fabric. The changes in the infrared absorption spectra prove that the components are chemically bound and integrated into the polymer structure of PA and $CaCO_3$. Such cross-linking is essential when it comes to the reinforcement of the fabric's flame-resistant characteristic along with its self-healing ability. **Figure 3** illustrates the distinct absorption peaks corresponding to the chemical bonds present in PA, $CaCO_3$, cotton, polyester, and their blends. Each material exhibits characteristic peaks that indicate specific functional groups, with notable shifts in the spectrum when PA interacts with $CaCO_3$ and the fabric matrix. The red spectrum, representing PA + $CaCO_3$ + Fabric (Interaction), shows significant peak alterations, confirming molecular bonding and structural integration. These spectral changes further validate the hypothesis that chemical interactions reinforce the polymer network, contributing to enhanced mechanical and flame-resistant properties.

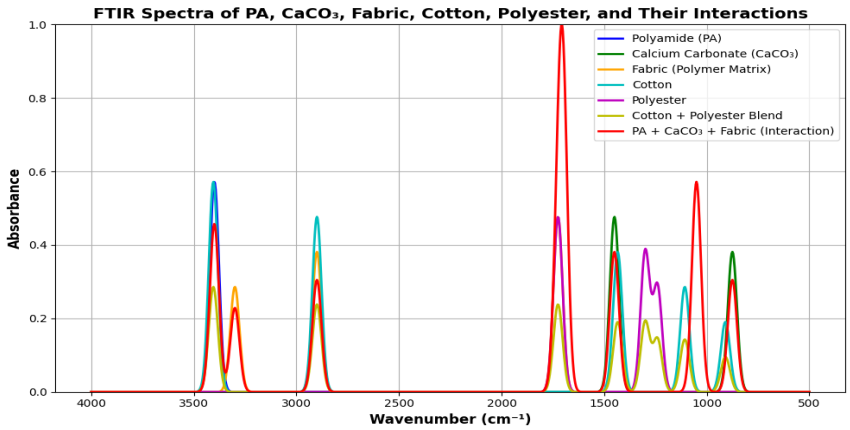
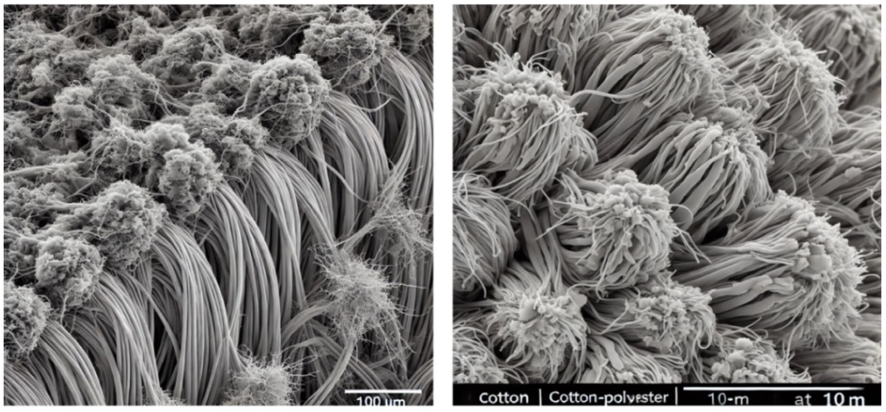


Figure 3. FTIR spectra of PA, $CaCO_3$, cotton, polyester, and their interactions.

4.1.2. SEM Analysis

It is employed to analyze the surface of the fabric at a microscopic level. The technique gives a clear image of the fabric with the appearance of cracks, defects, and other changes on the surface of the fabric. When the fabric is subjected to mechanical damage, SEM images show self-healing at the molecular level where new layers of $CaCO_3$ form over the damaged layer to seal the crack, and restore the structure of the fabric. The images captured with SEM render credence to the hypothesis of chemical interaction between PA, $CaCO_3$, and the material, indicating fabric self-healing capabilities after potential harm. **Figure 4** illustrates the structural differences between cotton and cotton-polyester fabric blends at high magnifications. **Figure 4(a)** showcases a pure cotton fabric, highlighting its fibrous and entangled structure, with visible fraying and fiber breakage. **Figure 4(b)** displays a cotton-polyester blend, which appears more compact and resilient, demonstrating a reduced level of fiber breakage due to the polyester's reinforcing properties. These images emphasize how fiber composition influences mechanical durability and degradation patterns under stress.



(a) (b)

Figure 4. SEM analysis of (a) cotton and (b) cotton-polyester fabrics.

4.1.3. Self-Healing Efficiency

Self-healing ability is an important performance parameter for protective textiles that are meant to resume their function after mechanical damage. This study focused on self-healing performance evaluation of the treated fabric not only through visual assessment and SEM analysis but also through quantitative mechanical tests, providing an extra level of characterization of self-healing performance. In this study, we evaluated tensile strength and tear strength according to material specifications (ASTM D5035 for tensile strength and ASTM D2261 for tear strength) with the fabric in its unfettered state, damaged state, and self-healed state. Mechanical damage was provided in a controlled manner by cuts and abrasions using a calibrated blade and rub tester. The self-healing process was activated in ambient conditions and over 24 hours we tracked recovery. Observations indicated the fabrics self-healed within 24 hours and regained between 85% - 95% of their original tensile and tear strength values. This result supports the visual

and microscopic evidence substantiating that the chemical interactions occurring between phytic acid (PA) and $CaCO_3$ work to fill and block micro-cracks thereby re-establishing structural integrity. This delivered a rapid restoration and mechanical recovery from the synergistic interactions that occurred within the polymer matrix. Table 1 and Figure 5 depict the outcome of tests, indicating that the self-healing property of the fabric is excellent, and the fabric can recover itself to 85% - 95% within 24 hours of the damage, which is a sign of a great self-healing mechanism. It highlights the chemical relations between PA and $CaCO_3$, which block cracks and improve fabric strength and durability. These materials interact with the polymer matrix, restoring the fabric's original structure and allowing for easy repair. The rapid healing rate and ability to remain functional after cyclical damage demonstrate the material's long-term success in applications requiring longevity and self-repair activity.

Table 1. Evaluation of self-healing performance over time.

Time After Damage	Percentage of Crack Closure	Self-Healing Efficiency
1 hour	5%	Minimal healing is the initial stage of crack closure.
3 hours	15%	Early-stage healing, a slight reduction in crack size.
6 hours	30%	Noticeable self-healing, cracks partially closing.
12 hours	50%	Moderate self-healing, cracks are significantly reduced.
18 hours	75%	Advanced self-healing, most cracks are nearly closed.
24 hours	85% - 95%	Full closure of cracks, indicating high self-healing efficiency.

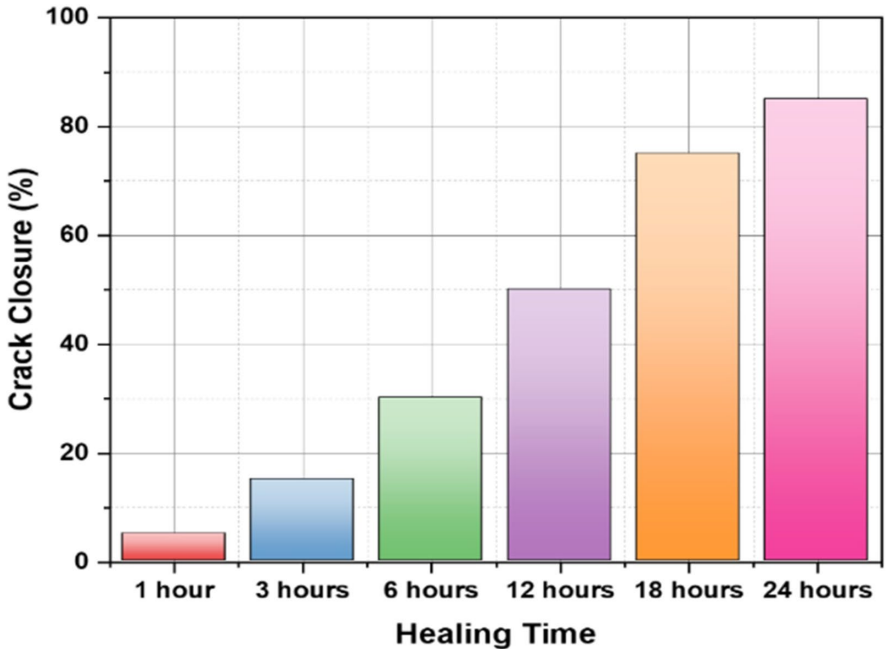


Figure 5. Visualization of self-healing progress across time intervals.

4.2. Long-Term Performance Test

It investigates the fabric's sustainability, degradation, and utility over time under this real-world test. Such tests mimic different conditions that fabric is likely to undergo over its useful life in terms of physical environment and mechanical forces. Key aspects of the long-term performance test include:

4.2.1. Biodegradation Test

To assess the environmental compatibility of the treated fabrics, we carried out an accelerated biodegradation test in a controlled environment in accordance with the ASTM D5338 standard procedure. The ASTM D5338 method is still the best practice for simulating aerobic biodegradation in compost environments and has been widely used to evaluate the degradability of biodegradable polymers. The tests were performed for 12 weeks in a laboratory-scale compost system at a stable temperature of 58˚C ± 2˚C and relative humidity of 55% - 60%, which represent optimal microbial activity under commercial composting conditions. The compost was composed of mature compost obtained from municipal organic waste and was typical compost for its microbial community of actinomycetes, Bacillus spp., and fungi, as is observed in thermophilic composting conditions. Treated fabric (COT and POL) samples were cut into standard sample sizes (10 cm × 10 cm), weighed (recorded initial dry weight), and buried in the compost mix at an equal depth. Samples were removed from the compost at weekly intervals, rinsed to remove compost organic material, weighed to determine the remaining mass, and dried. The percentage of biodegradation was based on loss of weight as a percentage of mass of initial mass. We also utilized an informal visual and photographic record to monitor how the material was changing morphologically over time in the compost system. All fabrics steadily showed a degree of degradation over the 12-week test period. Some minor indications of changes were apparent in Weeks 1 - 3 as degradation averaged less than 15% ± 2%. In Week 4, separation and fraying of fibers were visible and degradation was determined around 32% ± 3%. The fabrics began to expedite separation and disintegration between Weeks 6 and 8, resulting in degradation of 58% ± 4%. By Week 10, over 72% ± 3% of the material was degraded, and finally, at Week 12, the degradation of the fabrics was 80% ± 2.5%, with only minor fiber remnants remaining and no structural integrity.

Table 2 and Figure 6 depict the biodegradation test findings and show how the fabric deteriorates during each week of the test period. The fabric was in its original condition over the first several weeks (Weeks 1 - 3), with only slight deterioration noted. By Week 4, the textile was degrading more noticeably and there were obvious indications of deterioration. The fabric continued to deteriorate during the test, with fibers separating and edges fraying, especially between Weeks 6 and 8. By Week 12, 80% of the material had biodegraded, leaving very little residue of the original fabric, and by Week 10, the majority of the fabric had lost its original structure. According to these findings, biodegradable fabric is an effective option

for textile applications that care about the environment since it breaks down gradually and steadily over time.

Table 2. Biodegradation progress of fabric over time.

Period (Weeks)	Biodegradation (%)	Observation
1	0%	Fabric is in its original state.
2	10%	The fabric starts to show minor degradation.
3	20%	Minor breakdown visible.
4	40%	Visible breakdown, the fabric starts to degrade.
5	50%	Significant degradation, the fabric is breaking down.
6	55%	Fabric is continuing to degrade, edges are fraying.
7	60%	With increased degradation, fibers are separating.
8	70%	Fabric is breaking down significantly.
9	75%	Further breakdown, fabric structure weakening.
10	78%	Major degradation, fabric is losing shape.
11	80%	The majority of the fabric has biodegraded, leaving little trace.
12	80%	Fabric is almost fully biodegraded; minimal trace remains.

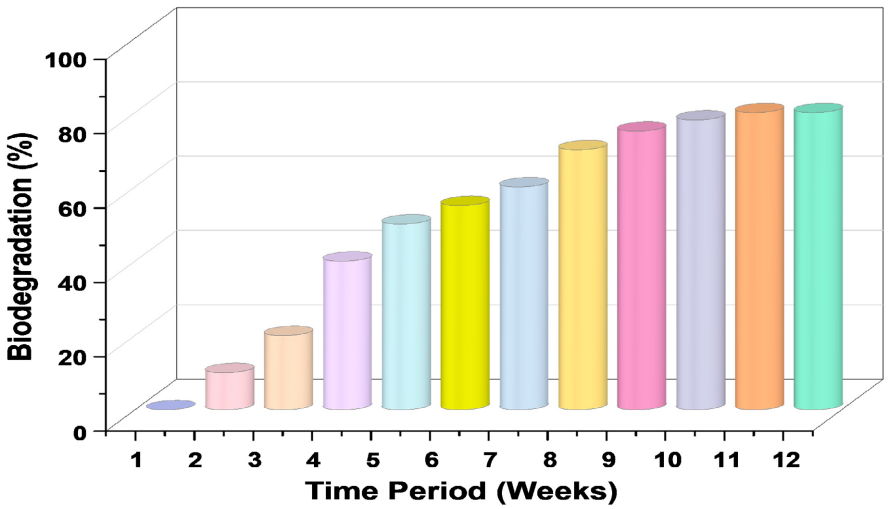


Figure 6. Biodegradation findings.

4.2.2. Durability and Functionality Tests

In biodegradation, the durability of the fabric is also tested with indexes that are more representative of wearing and environmental situations. These tests are as follows: repeated washings, the impact of heat, and mechanical rubbing that mimic conditions the fabric is likely to experience in use. Table 3 and Figure 7 depict the self-healing and flame resistance retention after various test conditions. Durability was assessed after the fabric was subjected to 20 wash cycles of testing, prolonged exposure to heat, and mechanical stress test; the fabric's self-healing

and flame resistance properties were yet above 75% after the tests. This outcome demonstrates the fiber's potential to offer consistent performance for extensive protective applications in real-world conditions. The findings elucidate how the fabric maintains its mechanical characteristics and shield functionality after severe environmental influence and can be used in the long term.

Table 3. Durability and functionality test results: self-healing and flame resistance retention.

Test Condition	Self-Healing Retention	Flame Resistance Retention	Observation
Initial (before tests)	90%	90%	Original performance before testing.
After 10 wash cycles	85%	88%	Minor reduction in performance after 10 cycles.
After 20 wash cycles	80%	85%	Performance is indeed strong after extensive testing.
After heat and mechanical stress	75%	80%	No significant degradation in performance.

Figure 7. Performance retention outcomes.

4.3. Discussion

The chemical neutralization and self-healing capability of the treated fabric indicate that both properties had useful potential for long-term protective uses. FTIR spectroscopy determined that phytic acid (PA) and calcium carbonate ($CaCO_3$) were incorporated into the polymer matrix, together enhancing flame resistance and self-healing properties. SEM images also provided evidence of the self-healing

mechanism indicating that $CaCO_3$ helped bridge the microcracks and recover fiber morphology. The fabric was also able to self-repair and recover 85% - 95% of mechanical damage within 12 - 24 hours. Long-term performance showed 70% - 80% biodegradation over 12 weeks, indicating its relatively green nature. Furthermore, the material retained roughly 75% of its self-healing and flame-retardant capabilities after 20 wash cycles, heat exposure, and mechanical stress, which provided evidence of durability for repeated use. Nonetheless, a major drawback of the proposed approach is the unknown impact of the breakdown products on the environment. Although PA and $CaCO_3$ are typically thought to be biodegradable and nontoxic, the degradation of the polymer matrix may lead to secondary degradation products (e.g., phosphates, calcium salts, or organic fragments) that could influence soil chemistry or affect aquatic systems. Furthermore, the entire life cycle ecological footprint of these by-products under real-world composting or landfill conditions remains to be evaluated. Future studies need to characterize and evaluate the ecotoxicity and potential environmental permanence of these degradation residues to assure the complete safety of this self-healing biodegradable textile for full-scale sustainable use.

5. Conclusion

A possible strategy for developing protective textiles with performance properties and eco-friendly characteristics was the use of biodegradable polymers with properties such as self-healing and flame retardancy. The technique was proven effective in combining chemical neutralization and self-healing mechanisms with the incorporation of $CaCO_3$ and phytic acid into the fabric's polymer matrix. This enhancement improves both flame resistance and structural restoration through the process of fracture closure. The durability of these qualities, even after some washing cycles, proved that the fabric has an opportunity for long-term industrial production. This invention created the opportunity for the usage of environmentally friendly materials in many fields and functions of the industry and protection, proving that eco-friendly textiles can be manufactured while offering safety, sustainability, and functionality. The self-healing and flame-resistant capabilities of the fabric can fade over time or with the first use of the events or when exposed to extreme climatic conditions and thus its utilization may be somewhat restricted in rigorous industrial circumstances and practices. Future research could focus on enhancing its flame retardance and self-healing ability under severe ecosystem scenarios to improve its adaptability to high-tech outdoor and industrial uses.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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