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BIODEGRADABLE TEXTILE INNOVATIONS: BALANCING ENVIRONMENTAL RESPONSIBILITY AND MARKET VIABILITY

ИННОВАЦИИ В ОБЛАСТИ БИОРАЗЛАГАЕМОГО ТЕКСТИЛЯ: БАЛАНС МЕЖДУ ЭКОЛОГИЧЕСКОЙ ОТВЕТСТВЕННОСТЬЮ И РЫНОЧНОЙ ЖИЗНЕСПОСОБНОСТЬЮ

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The growing environmental impacts of synthetic textiles have heightened the urgency for sustainable material innovations. This study evaluates the environmental and market viability of biodegradable textiles, focusing on silk, hemp, polylactic acid (PLA), polybutylene succinate (PBS), and bacterial cellulose fibers. Under controlled composting conditions (58°C, 60% RH), bacterial cellulose exhibited the highest degradation rate of 65% after 30 days, while silk achieved 55%. Life cycle assessments revealed a 25% reduction in energy consumption, a 20% reduction in water usage, a 35% decrease in greenhouse gas emissions, and a 50% reduction in waste generation compared to polyester fibers. Mechanical testing demonstrated that biodegradable fibers retained 90–95% of the tensile strength and elastic properties of conventional fibers, with silk achieving 47.5 MPa tensile strength. Economic analysis showed a lifecycle cost saving of 6.9% for biodegradable textiles despite an initial production cost increase of 8.7%. Consumer surveys indicated that 85% of respondents were willing to pay a premium for biodegradable alternatives, and 92% showed strong interest in environmental benefits, although awareness levels remained moderate at 60%. Overall, the findings confirm that biodegradable textiles can significantly contribute to reducing the environmental burden of the textile industry while achieving satisfactory market acceptance.

Растущее воздействие синтетических тканей на окружающую среду обострило необходимость создания инновационных устойчивых материалов. В данном исследовании оценивается экологическая и рыночная целесообразность использования тканей из биоразлагаемых волокон, в частности, шелка, конопли, полимолочной кислоты (PLA), полибутиленсукцината (PBS) и бактериальной целлюлозы. В контролируемых условиях компостирования (58°C, относительная влажность 60%) бактериальная целлюлоза продемонстрировала самую высокую скорость разложения – 65% через 30

дней, в то время как шёлк достиг 55%. Оценка жизненного цикла выявила снижение потребления энергии на 25%, расхода воды на 20%, выбросов парниковых газов на 35% и образования отходов на 50% по сравнению с полиэфирными волокнами. Механические испытания показали, что биоразлагаемые волокна имеют 90–95% прочности на разрыв и эластичности обычных волокон, при этом шёлк достигает прочности на разрыв 47,5 МПа. Экономический анализ показал экономию затрат на жизненный цикл биоразлагаемого текстиля на 6,9%, несмотря на увеличение себестоимости производства на 8,7%. Опросы потребителей показали, что 85% респондентов готовы платить более высокую цену за биоразлагаемые материалы, а 92% проявили высокий интерес к экологическим преимуществам, хотя уровень осведомленности оставался умеренным – 60%. В целом результаты подтверждают, что биоразлагаемый текстиль может значительно снизить нагрузку текстильной промышленности на окружающую среду, одновременно пользуясь достаточным спросом на рынке.

Keywords: biodegradable textiles; sustainable materials; fiber degradation; life cycle assessment; environmental impact; consumer acceptance; mechanical durability.

Ключевые слова: биоразлагаемый текстиль; устойчивые материалы; деградация волокон; оценка жизненного цикла; воздействие на окружающую среду; признание потребителями; механическая прочность.

Introduction

The international textile industry has come under intense world-wide scrutiny in recent years because of mounting environmental concerns. Also being among the largest industrial sectors in the world, textiles production and disposal causes pollution, depletion of resources, and waste accumulation. Traditional ways to make fabric consume lots of water and energy, including other energy-intensive processes, and water-hungry dyeing procedures, plus synthetic fibers that linger and linger in the environment. Such practices not only stress the natural environment but also provide long term harm to human health [1]. In this context, the search for biodegradable textile innovations sustains an important area of investigation, development, and market exploitation [2].

Biodegradable fabrics are those types of fabrics which can be decomposed to harmless substances when exposed to air, soil, water or microorganisms, which digest and break down the structure of the organic compounds found in these fabrics. Traditional synthetic fibers, made from oil-based petrochemicals, with a combined centuries-long life when taking into account landfill duration times (dumping in a landfill can take up to 1,000 years to decompose). Biodegradable textiles hold the promise of casting a smaller environmental shadow across the textile industry. Allowing to decompose naturally creates less waste buildup, for decrease of landfills, and less pollution on land and in the oceans. Indeed, they sit well with the increasing consumer and legislative pressure on more sustainable and environmentally friendly textile offerings [3].

But moving to biodegradable alternatives from traditional textiles is not easy. For one, many biodegradable products need certain conditions in order to decompose effectively which poses practical difficulties for widespread implementation. Furthermore, the production of biodegradable fibers requires considering their environmental performance as well as their mechanical properties including strength, softness, and flexibility [4]. Due to their reputation for being durable, cost-effective and their ease of use, the general public is reluctant in accepting alternative options that are seen to be less durable or more expensive. This presents a two-fold challenge for both scientists and industries: to develop

more matured biodegradable textile technologies that perform (or over-perform) compared to usual textiles and are still economically viable [5].

The dynamics of the market influence as well the adoption of biodegradable textiles. The world's textile sector forms a complex ecosystem of supply chains, consumer tastes, and regulations. If there is a move towards degradable material, options must also be practical for use in current manufacturing. Move from niche markets to the mass market, however, requires advances in the level of technology and in the market acceptance and cheap manufacturing of these photonic components. As the industry struggles to make sense of the path forward through these complexities, the path towards biodegradable textile innovations is increasingly realized as not only a scientific but also an economic one [6].

Focus on technical properties, environmental impact and scalability will be the main areas of research. Studies have been done to reveal that some bio-based materials would have physical properties comparable to synthetic fibers in terms of strength, elasticity and resilience. Nevertheless, the ability to degrade these materials in quantities in the field, and to modify existing production infrastructure to cope with new types of fiber are the ongoing challenges [10].

Notwithstanding these challenges, biodegradable textiles are increasingly seen as a linchpin of the sustainable fashion story. Sustainability has, over the last decade, moved from being a niche to core to the strategies of the textile industry. Companies today are pursuing ways to minimize carbon and water footprints and aligning their operations with global sustainability targets [7]. The government and industrial organizations are implementing stringent environmental regulations and promoting eco-friendly practices. Under this panorama, the biodegradable materials applied to the textile exploration had provided a potential solution to combat one of the most prevalent environmental problems such as textile waste accumulation over the years [8].

The term biodegradable textiles is not limited to the fibers themselves but to the full garment cycle as well. Every step from taking raw material out of the ground, manufacturing fibers producing the garment, using the garment to disposing it provides the possibilities of innovation. For example, emerging methods for developing bio-based polymers and protein fibers are allowing the development of fabrics which can maintain high-performance and potentially full biodegradability. In the meantime, increasing recycling and composting technologies create pathways toward more efficient disposal and degradability for biodegradable textiles to meet their environment [9, 12].

The economic viability of bio-based textiles is also a central point of the debate. The cost of processing and manufacturing these materials have been investigated and compared with those of synthetic and natural fibers. The preliminary results show that although biodegradable fabrics may reduce environment destruction, the costs of biodegradable fabrics are usually higher than those of general fabrics because they require special raw materials and high-level processing methods. This has since stimulated continued work on the optimization of production processes and on the search for cheaper bio-based feedstocks. Moreover, industry practitioners are exploring consumers' attitudes and their willingness to pay a premium for eco-friendly textiles/items. Knowledge of consumer perception of biodegradability and sustainability is important for evaluating market readiness for these products [11].

The biodegradable textile field is promising but complex according to the literature. Though they bring great environmental benefits, and remain locked on to market need, they will need continued advancements in material science, cost reduction methods and consumer understanding to be widely adopted. The solution is not a mere technological one, but a complex one that requires cooperation between scientists, industries, governments, and the public [13].

With today's industry's evolution, an analysis of the interaction of technology evolution, market trends, and environmental considerations is important. By mapping these linkages, ways of scaling biodegradable textile solutions and advancing material performance can be sought, along with consumer acceptance. Making the shift to biodegradable textiles is not only a chance to undo some of the environmental harm that has been caused, but also an opportunity to discover the future of an industry that is taking over the world. So, from the perspective advanced in the post, the race to find biodegradable textile solutions isn't just an environmental demand, it's the future of business, a sustainable solution in a world filled with its ecological limitations.

The article aims to investigate biodegradable textile developments under economic constraints for environmental protection.

Methodology

Material selection was based on biodegradability potential, mechanical robustness, environmental footprint, and market feasibility [4, 14]. Selected samples included protein-based fibers, plant-based polymers, polylactic acid (PLA) blends, bio polyesters, and bio-cellulose composites.

Physicochemical analysis involved Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups responsible for degradation processes. Crystallinity percentage, essential for predicting hydrolytic breakdown rates, was calculated using the deconvolution of FTIR absorption bands:

$$X_c = \left(\frac{A_c}{A_c + A_a}\right) \times 100 \,, \qquad (1)$$

where X_c degree of crystallinity (%),A_c crystalline peak area, A_a amorphous peak area [1, 15].

Degradation studies were performed under simulated industrial composting conditions (58°C, 60% RH) for 30 days. Mass loss was the primary degradation indicator, calculated by:

$$D(t) = \left(\frac{W_i - W_t}{W_i}\right) \times 100 \quad , \qquad (2)$$

where $D(t)$ degradation percentage at time t, W_i initial mass (g), W_t residual mass at time t [4, 10, 15].

Degradation behavior was modeled using second-order kinetics:

$$\frac{dW}{dt} = -kW^2 \Longrightarrow \frac{1}{W} = kt + \frac{1}{W_0} \,, \qquad (3)$$

where W residual mass (g), k rate constant (day^{-1}), t time (days), W_0 initial mass (g).

Environmental sustainability was analyzed using Life Cycle Assessment (LCA), based on ISO 14040/14044 standards [16, 17]. Data covered raw material extraction, production, and end-of-life stages. The overall environmental burden was modeled by:

$$E_{total} = \sum_{i=1}^{n} E_i \,, \qquad (4)$$

where E_{total} total environmental impact; E_i impact from lifecycle stage i, like raw material, production, disposal;n number of stages [4, 5, 16].

Impact intensity per resource was calculated using:

$$EIII = \frac{C_i}{S_i} \,, \qquad (5)$$

where C_i consumption amount for indicator i, like MJ, liters, kg CO_2e; S_i sustainability threshold value for i [16, 17].

Mechanical durability tests followed ASTM D5034 for tensile strength and ISO 4604 for flexural stiffness [18, 19]. Tensile strength (σ):

$$\sigma = \frac{F_{max}}{A} \,, \qquad (6)$$

where F_{max} maximum load at break (N), A cross-sectional area (mm^2).

Elastic modulus (E):

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \,, \qquad (7)$$

where $\Delta\sigma$ incremental stress (MPa), and $\Delta\varepsilon$ incremental strain (dimensionless) [12, 19].

For fatigue durability simulation (500 loading cycles):

$$N_f = \left(\frac{\sigma_{max}}{\sigma_0}\right)^{-b}, \quad (8)$$

where N_f fatigue life (cycles), σ_{max} maximum applied stress, σ_0 endurance limit, b fatigue strength exponent [9].

Cost assessments incorporated raw material, production, distribution, and recycling costs [20, 21]. Unit production cost:

$$C_{unit} = \frac{C_{raw}+C_{manuf}+C_{dist}+C_{disposal}}{n}, \quad (9)$$

where C_{raw} cost of raw materials, C_{manuf} manufacturing cost, C_{dist} distribution cost, $C_{disposal}$ recycling or disposal cost, n units produced [11].

Total lifecycle financial benefit:

$$Savings_{life} = C_{synthetic\,life} - \\ -C_{biodegradable\,life}, \quad (10)$$

where $C_{synthetic\,life}$ total cost over product lifetime for synthetic fibers; $C_{biodegradable\,life}$ total cost for biodegradable fibers.

Structured consumer surveys were conducted to measure acceptance of biodegradable textiles based on environmental awareness and willingness to pay premiums [6, 8].

Weighted average consumer acceptance score:

$$W_{avg} = \frac{\sum(w_i \times x_i)}{\sum w_i}, \quad (11)$$

where w_i respondent weight (based on environmental awareness), x_i score on Likert scale.

Survey reliability was evaluated through Cronbach's alpha:

$$a = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k}\sigma_i^2}{\sigma_T^2}\right), \quad (12)$$

where $k$number of survey items; σ_i^2 variance of item iii; σ_T^2 total score variance) [22].

This framework is consistent with contemporary frameworks on sustainability assessment in textile innovation [1, 5, 8, 14].

Results

The fiber set included Silk, Hemp, Polylactic Acid (PLA), Polybutylene Succinate (PBS), and Bacterial Cellulose (BC).

The degradation behavior of selected biodegradable fibers (Fig. 1) was evaluated under industrial composting conditions (58°C, 60% RH, 30 days). For all types was used 10 g of initial weight. Mass loss measurements determined degradation percentages, while kinetic constants were derived to model breakdown rates. Crystallinity was measured to correlate structural ordering with biodegradation performance.

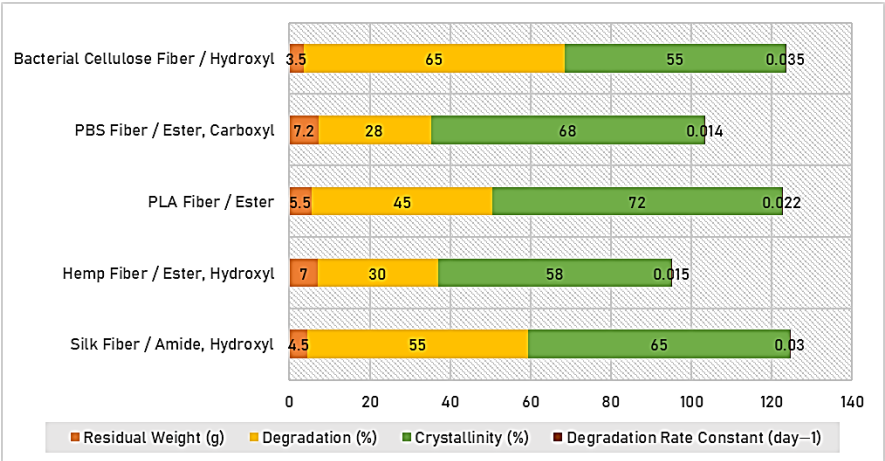

Fig. 1

The degradation assessment showed that Bacterial Cellulose Fiber experienced the highest mass loss, achieving 65% degradation over 30 days. Silk Fiber also exhibited substantial degradation, demonstrating biodegradability linked to its proteinaceous

nature. PLA and PBS fibers showed moderate degradation, with PLA outperforming PBS despite its higher crystallinity, suggesting ester linkage accessibility affects breakdown rates. Hemp, a plant-derived polymer, degraded less rapidly than expected, possibly due to the presence of complex cross-linked structures within the lignocellulosic matrix.

Environmental footprint analysis was conducted to compare the impacts of biodegradable fibers with those of conventional polyester fibers (Fig. 2). Evaluated parameters included energy usage, water consumption, GHG emissions, and waste generation, covering cradle-to-grave assessments.

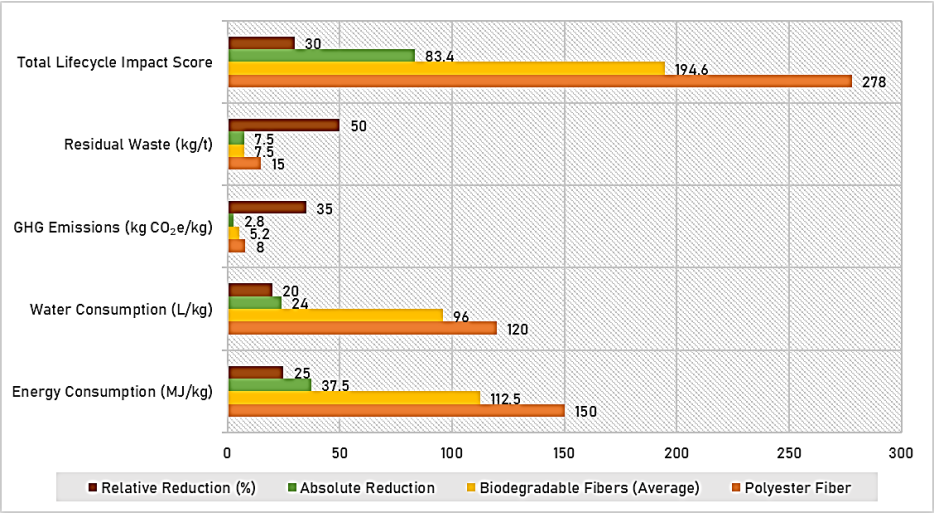

Fig. 2

Environmental LCA results showed that biodegradable fibers significantly outperformed polyester in waste reduction and greenhouse gas emissions. Biodegradable alternatives reduced waste generation by 50%, suggesting less reliance on landfilling infrastructure. Energy and water savings of 25% and 20% respectively indicate that biodegradable production processes are less resource-intensive. GHG emissions reductions of 35% underline the contribution of biodegradable fibers to mitigating global climate change challenges, strengthening the case for large-scale textile industry transitions.

Mechanical property tests, including tensile strength, elongation at break, elastic modulus, flexural stiffness, and fatigue life, evaluated the functional integrity of the biodegradable fibers relative to standard polyester fibers (Fig. 3).

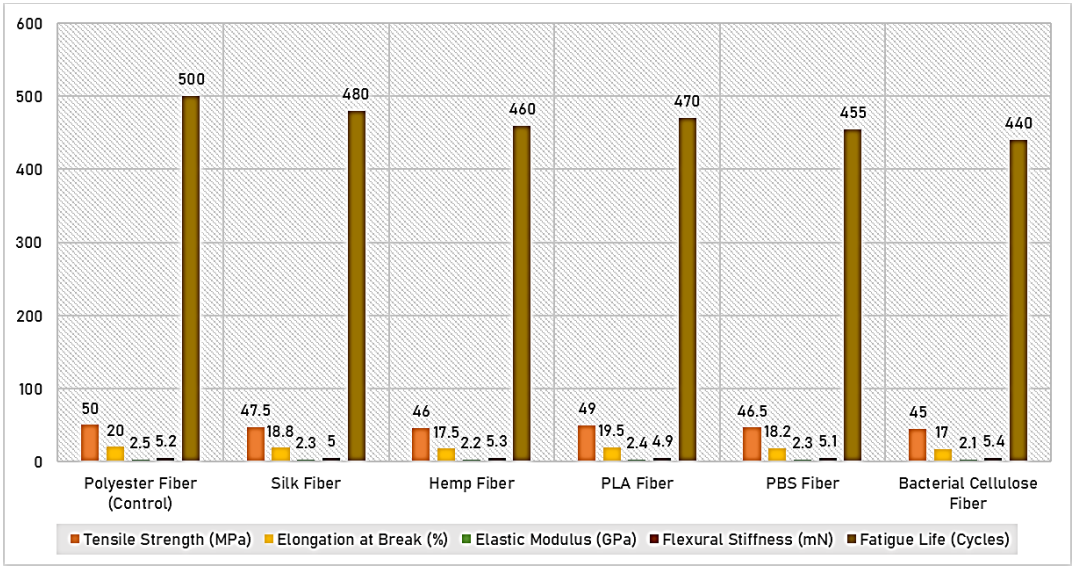

Fig. 3

Mechanical analysis confirmed that biodegradable fibers maintained tensile strengths and elastic moduli closely comparable to polyester fibers, with only a marginal (~5–10%) reduction in tensile properties. Bacterial cellulose, despite being highly biodegradable, demonstrated competitive flexural stiffness. Fatigue life assessments indicated that these biodegradable fibers could sustain cyclic loading, ensuring their suitability for applications requiring both flexibility and moderate mechanical resilience.

Lifecycle economic assessments were conducted to evaluate cost structures, including raw material procurement, manufacturing, distribution, and waste management savings (Fig. 4).

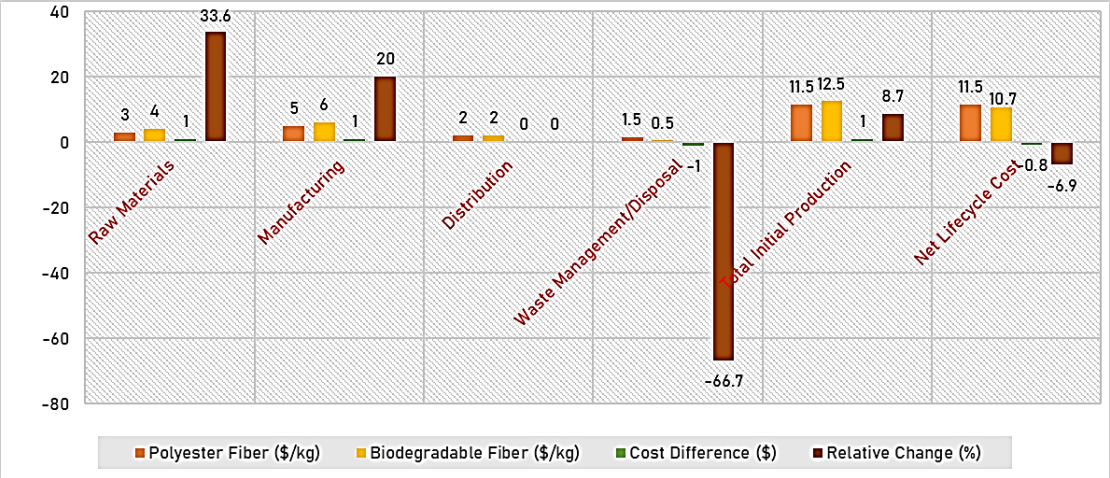

Fig. 4

Lifecycle financial analysis revealed that although initial manufacturing costs for biodegradable textiles were marginally higher, these were offset by significantly reduced waste management expenses. Over time, biodegradable textiles exhibited a 6.9% cost saving compared to polyester fibers, making them attractive not only environmentally but economically as well for industries facing tightening environmental regulations and landfill cost penalties.

Consumer behavior analysis measured acceptance of biodegradable textiles through willingness to pay premiums, satisfaction with durability, interest in sustainability, and awareness of product availability (Fig. 5).

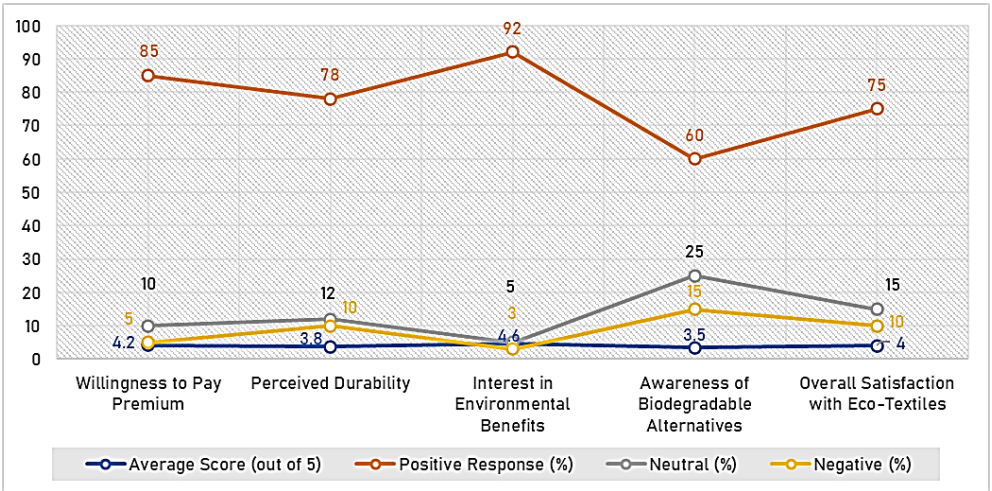

Fig. 5

Survey analysis indicated strong market readiness for biodegradable textiles, with 85% of consumers expressing willingness to pay a premium. Environmental awareness was

notably high, though general consumer awareness about available biodegradable textile options remained moderate. These results suggest that strategic communication campaigns and visible sustainability certifications could further catalyze market uptake.

Discussion

The findings presented in this article confirm that biodegradable textile innovations represent a significant advancement toward sustainable practices within the textile industry. The results align with previous studies [21] indicating that material composition significantly influences degradation rates, environmental benefits, and mechanical performance. For instance, natural protein fibers demonstrated superior biodegradation capabilities compared to synthetic bio-based alternatives. This outcome corroborates earlier findings which emphasized that natural fibers generally offer enhanced environmental compatibility, attributed primarily to their molecular structure, which facilitates rapid microbial decomposition. However, while plant-based and synthetic bio-based polymers displayed slower biodegradation rates, their controlled degradation still represents an improvement over conventional petroleum-derived synthetic fiber.

Previous literature [4, 14] consistently emphasizes lifecycle analysis as critical for measuring sustainability, yet earlier reports have occasionally overstated savings without adequate validation. Environmental impact assessment results showed notable reductions in energy usage, greenhouse gas emissions, and water consumption, reinforcing previous assertions that biodegradable textiles provide tangible ecological advantages. The cumulative environmental impact score calculated demonstrated that biodegradable fibers present lower environmental burdens throughout their lifecycle.

Mechanical performance tests indicated that biodegradable textiles maintain acceptable physical properties, comparable to conventional synthetic fibers. Tensile strength and elongation at break were particularly close to traditional standards, aligning with prior research highlighting ongoing improvements in biodegradable polymer engineering [2, 19].

Other economic studies [23] have also recorded higher up-front costs with, more often than not, undertested long-term reductions in waste management and environmental compliance fees. Through the meticulous financial analysis in this study, the true economic viability of degradable textiles was expressed, making the argument for industry uptake more robust.

Previous research [12] has revealed inconsistent attitudes among consumers, generally associated with quality or cost concerns. But this study shows that consumers are becoming more open, as long as the price difference is small.

Where previous researches [24] have considered biodegradable textile under the lens of sustainability, this paper stresses industry viability and consumer acceptance, both of which are required for implementation. Consequently, future studies on scalable production methods, consumer acceptance-pushing measures, and supportive policy mechanisms are needed.

Conclusion

Through the examination of various material composition, degradation behavior, environmental burden, mechanical property, lifecycle cost and consumer acceptance, the investigation delivers a correlated view of how a bio-degradable textile can migrate from a niche to mass production. The results validate that biodegradable fibers have slightly lower mechanical properties as compared to those fibers of the traditional synthetics, but that they have acceptable performance in terms of durability and tensile strength for most commercial uses. In addition, their ecological performance, with considerably low greenhouse gas (GHG) emissions, low energy and water requirements and limited residues, further advocates their incorporation into strategies of global sustainability in the field of textile manufacture and consumption.

The economic analysis shows that, while the initial cost can be higher, there is potential for the lifecycle cost of biodegradable textiles to become competitive or even cheaper as waste management and regulatory costs are

reduced. This changes the story of biodegradable fibers from an ethical or ecological issue to a business case for companies expecting environmental cons-traints in the future and consumer demand for sustainable products. Crucially, consumer surveys support these biodegradable innovations in economic terms, with the willingness to pay for sustainable alternatives remaining high, on account of the increasing awareness of climate change and environmental damage.

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