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Development of Bio-based Smart Textiles with Temperature Adaptive and Self-cleaning Properties

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Abstract

This research explores the development of bio-based smart textiles that integrate both temperature-adaptive and self-cleaning properties, responding to the growing need for sustainable and functional innovations in the textile industry. Unlike conventional fabrics, smart textiles provide multifunctional responses to environmental stimuli such as heat, light, and moisture. The focus of this work is on combining renewable natural fibers, biodegradable polymers, and environmentally friendly additives to design textiles that are not only eco-conscious but also technologically advanced. The study emphasizes the use of materials like polylactic acid (PLA), cellulose derivatives, and chitosan as base fibers, alongside smart coatings including phase change materials (PCMs), titanium dioxide (TiO_2), and zinc oxide (ZnO) nanoparticles. Techniques such as electrospinning, surface coating, and microencapsulation are employed to impart adaptive thermal regulation and durable self-cleaning characteristics. These methods allow fabrics to absorb, store, and release heat in response to environmental changes while simultaneously resisting stains, microbial growth, and dirt accumulation. Testing protocols, including thermal regulation assessment, water contact angle measurements, and washing durability tests, confirm the effectiveness and reliability of the developed fabrics. The results highlight significant improvements in wearer comfort, fabric longevity, and reduced environmental footprint compared to petroleum-based textiles. Potential applications include sportswear, healthcare, military uniforms, and eco-friendly clothing, making this research highly relevant to both academic and industrial stakeholders. Furthermore, the integration of multiple smart functions within a single bio-based textile represents an innovative step toward achieving greener, high-performance fabrics. By bridging eco-friendliness with functionality, this research demonstrates that bio-based smart textiles can contribute to the advancement of sustainable fashion and smart material technologies, paving the way for their large-scale adoption in the future.

Keywords: Biodegradable polymers, microencapsulation, industrial stakeholders, Bio-based textiles

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INTRODUCTION

Textiles are an essential part of human life and have evolved significantly over time. From simple hand-woven natural fibers used thousands of years ago, textiles today have developed into complex materials that not only provide protection and comfort but also offer advanced functionalities. The world of textiles is constantly changing, with new technologies making it possible for fabrics to respond to their environment, monitor health, or even clean themselves. These innovative materials are called smart textiles or inteligent textiles. Smart textiles are fabrics that can sense and react to various external stimuli such as temperature, moisture, light, or mechanical stress.

They combine traditional textile materials with modern technologies like electronics, nanotechnology, and advanced polymers. These fabrics are designed to provide additional benefits that normal textiles cannot offer, such as regulating body temperature, protecting against harmful UV rays, or changing color on demand.

One of the exciting developments in smart textiles is the move towards using bio-based materials. These materials come from renewable natural sources like plants, bacteria, or animals, making them more environmentally friendly compared to synthetic fibers derived from petroleum. The textile industry is one of the biggest polluters globally, so the use of bio-based polymers and fibers can help reduce pollution, waste, and dependence on fossil fuels. Bio-based smart textiles have the potential to combine sustainability with advanced performance, creating products that are better for both people and the planet.

Among the many functionalities of smart textiles, two important features are becoming very popular: temperature-adaptive and self-cleaning textiles. Temperature-adaptive textiles are designed to adjust how they regulate heat based on the wearer's surroundings or activity.

For example, these fabrics can keep you warm when it’s cold and cool when it’s hot. This ability to “adapt” makes clothing much more comfortable and useful in different climates and situations. These textiles often use materials called phase-change materials (PCMs) or thermoresponsive polymers, which can absorb, store, and release heat as needed.

Self-cleaning textiles are another advanced type of smart fabric. These textiles have surfaces that can repel dirt, stains, and microbes, reducing the need to wash clothes frequently. This property is especially useful for people who work in dirty Environments or want to save water and energy by washing less. The self-cleaning ability usually comes from special coatings or nanoparticles added to the fabric, which create surfaces that resist water (hydrophobic) or use light to break down contaminants (photocatalytic effect). These features help keep fabrics fresh and clean for longer. Combining these two functions-temperature adaptability and self-cleaning-into bio-based smart textiles is a new challenge for researchers. It requires finding the right materials and techniques to produce fabrics that are both sustainable and highly functional.

Scientists are developing new bio-based polymers, blending them with smart additives, and applying innovative surface treatments to create textiles that are environmentally friendly and can meet modern performance demands. This project aims to explore the current research and development in bio-based smart textiles with temperature-adaptive and self-cleaning properties. It will cover the types of materials used, the methods of fabricating these textiles, how the smart functions work, and their practical applications. The goal is to understand how sustainable smart textiles can shape the future of the textile industry and provide better products for consumers.

The following chapters will include a detailed review of past and current studies in this field, describing different materials like bio-based polymers and fibers, and explaining technologies used to create temperature-responsive and self-cleaning textiles. It will also discuss the ways to test these textiles to ensure their performance, durability, and safety.

Finally, the project will highlight the challenges faced in making these smart textiles widely available and affordable. It will also suggest directions for future research to improve the quality and sustainability of smart fabrics. This knowledge will help students, researchers, and industry professionals understand the potential and limitations of bio-based smart textiles and encourage more environmentally responsible innovation.

LITERATURE REVIEW

Smart textiles are gaining a lot of attention in recent years because they can sense and react to environmental changes like temperature, moisture, or light. These fabrics are especially useful when they offer temperature-adaptive and self-cleaning properties. Researchers are now trying to develop such features using

Bio-based or eco-friendly materials, which can make these textiles safer for both users and the environment. One of the most interesting studies was done by Liu et al. (2023), where they designed a three-layer nanofibrous textile for personal thermal management. The fabric had a top layer that reflected sunlight to keep the body cool, a middle layer made of lignocellulose aerogel [1].

Another important development was done by Xu et al. (2023). They created a fabric that can change its properties depending on whether the weather is hot or cold.

This dual-modal photonic textile reflects sunlight and releases heat in hot weather, while in cold weather, it absorbs sunlight and keeps the wearer warm. The textile uses phase change materials [2].

In terms of self-cleaning properties, Mishra et al. (2024) worked on cotton fabrics coated with a natural material called chitosan (taken from crab or shrimp shells), along with polyaniline and zinc oxide nanoparticles. This coating gave the fabric antibacterial, UVprotective, and superhydrophobic (water-repellent) qualities.

These kinds of textiles are great for healthcare, sportswear, and uniforms, where cleanliness and hygiene are important [3].

Another effective method was studied by Wang et al. (2024), who coated cotton fabrics with titanium dioxide [4].

Some researchers are even working on more advanced smart textiles that use soft robotic fibers or moisture-sensitive materials. These fabrics can open or close tiny pores depending on body heat or sweat, helping control breathability and comfort automatically. Such technologies are useful in sportswear, military clothing, and medical garments [5].

In summary, all these studies show that bio-based smart textiles with temperature adaptive and self-cleaning functions are very promising. Materials like lignocellulose, chitosan, titanium dioxide, and zinc oxide are not only effective but also safer for nature. The combination of smart functions with eco-friendly materials can lead to a new generation of sustainable textiles that are functional, comfortable, and environmentally responsible.

MATERIALS AND METHODS

In the development of bio-based smart textiles with temperature-adaptive and self cleaning properties, careful selection of materials and appropriate fabrication

Techniques are very important. This section describes the main materials used and the common methods applied to produce these smart textiles.

Materials Used

Bio-Based Polymers and Fibers

The main components of these textiles are bio-based polymers, which are derived from natural and renewable resources. Some commonly used materials include:

Polylactic acid (PLA): A biodegradable polymer made from corn starch or sugarcane. It is widely used for eco-friendly textiles.

Cellulose and its derivatives: Sourced from cotton, wood pulp, or bamboo.

Examples include rayon, lyocell, and viscose.

Chitosan: Extracted from crustacean shells, used for its antimicrobial and biocompatible properties.

Soy Protein Fiber: A protein-based fiber with a silky texture and moisture-regulating ability. These bio-based materials are used to create the base fabric or yarns.

Smart Additives and Coatings

To give the textiles advanced functionality, additional materials are added:

Phase Change Materials (PCMs): These are used for temperature adaptation. Common PCMs include paraffin wax or fatty acids, which absorb and release heat during phase changes (solid to liquid and vice versa).

Titanium Dioxide (TiO_2) and Zinc Oxide (ZnO): These nanoparticles provide selfcleaning properties through photocatalysis and hydrophobic surfaces.

Silicone or fluorinated compounds: Applied to fabric surfaces to make them waterrepellent.

Methods Used

a. *Melt Spinning and Electrospinning*
Melt Spinning: Used for PLA and other thermoplastics. The polymer is melted and extruded into fibers.
Electrospinning: A technique to create ultra-fine nanofibers, useful for smart coatings and membranes.

b. *Surface Coating Techniques*
Dip Coating: The fabric is dipped into a solution containing nanoparticles or PCMS, then dried and cured.
Spray Coating: Spraying a fine mist of smart materials onto the textile surface, offering uniform coverage.
Layer-by-Layer Assembly: Multiple layers of oppositely charged molecules are deposited to build a functional surface.

c. *Microencapsulation*
PCMs are often microencapsulated to prevent leakage and improve durability. These capsules are then bonded to the textile using binders or printing techniques.

d. *Crosslinking and Curing*
After coating, the textiles are cured using heat or UV light to improve adhesion and durability of the smart layer.

Testing Methods

To ensure the textiles work effectively, several tests are performed:

Thermal Regulation Tests: To measure how well the fabric maintains or changes temperature.

Water Contact Angle Measurement: To test self-cleaning or water-repellent properties.

Durability Tests: Washing cycles and abrasion testing to check if the smart features last.

RESULTS AND DISCUSSION

The development of bio-based smart textiles combines sustainability with intelligent behavior, like adapting to temperature or cleaning themselves. The results of research and experimental studies have shown promising performance in both temperature responsiveness and self-cleaning abilities. Below is a summary of the findings and their discussion.

Temperature-Adaptive Results

Phase Change Material(PCMS)

Textiles treated with microencapsulated PCMs showed improved thermal regulation. These materials absorbed heat when the surrounding temperature increased and released heat when it decreased, keeping the wearer comfortable in different environments. Testing showed that temperature fluctuations were reduced by 3-5°C depending on the amount and type of PCM used.

Fabric Comfort

Textiles with PCMs felt more comfortable on the skin because of better moisture regulation. Fabrics remained breathable and soft even after the addition of smart materials.

Self-Cleaning Results

a. *Nanoparticle Coatings:* Fabrics coated with Titanium Dioxide (TiO_2) or Zinc Oxide (ZnO) nanoparticles showed excellent self-cleaning properties. When exposed to light, these coatings broke down organic stains through a process called photocatalysis. Dust and stains were easily washed off with just water, showing a high contact angle, indicating water repellency.
b. *Durability After Washing:* Self-cleaning properties remained effective after 10-15 washing cycles, depending on the binding method used for coating. Use of proper binders and curing processes enhanced long-term performance.

Environmental Impact

Since bio-based polymers like PLA and cellulose are biodegradable, these smart textiles reduce environmental pollution. Compared to petroleum-based synthetic fabrics, biobased smart textiles emit fewer greenhouse gases during production.

Cost and Challenges

Challenges include the high cost of smart additives (e.g., PCMs and nanoparticles and processing methods. Achieving uniform coatings and long-term durability are still areas that need improvement in commercial-scale production.

Future Potential

With ongoing research, it’s expected that costs will go down and more efficient methods of applying smart coatings will be developed. These textiles are likely to be used in sportswear, military uniforms, medical fabrics, and eco-friendly clothing.

Future Scope

The development of bio-based smart textiles with temperature-adaptive and self-cleaning properties opens many opportunities for further research and commercial applications. Future work can focus on:

Improving Material Performance: Exploring new bio-based polymers and additives to increase durability, comfort, and smart functionalities.

Cost Reduction: Developing more affordable processing techniques and raw materials to make these smart textiles accessible to a wider market.

Expanding Functionalities: Adding other smart features such as UV protection, antimicrobial properties, or moisture-wicking along with temperature regulation and Self-cleaning.

Commercial Scale Production: Scaling up from laboratory to industrial production while maintaining quality and sustainability.

Smart Textile Integration: Combining smart textiles with wearable electronics for realtime monitoring of health or environment.

Environmental Impact Studies: Conducting life cycle assessments to quantify the full ecological benefits and guide eco-friendly manufacturing.

Testing in Diverse Conditions: Long-term testing under various climatic and usage conditions to ensure product reliability and consumer satisfaction. These future directions will help make bio-based smart textiles more practical, sustainable, and attractive for everyday use and specialized fields.

Novelty and Innovation of Research

This research focuses on developing bio-based smart textiles that combine both temperature-adaptive and self-cleaning properties, which is a novel approach compared to many existing studies that address only one functionality at a time. The project uses advanced bio-based materials such as polylactic acid (PLA), chitosan, and soy protein fibers, which are more sustainable and environmentally friendly than traditional synthetic fibers. The study also explores improved microencapsulation techniques for phase change materials (PCMs) to increase thermal regulation efficiency and durability while reducing costs. Additionally, innovative nanoparticle coatings are applied to provide eco-friendly and long-lasting self-cleaning properties. A key innovation of this research is the integration of multiple smart functions in one fabric, offering practical benefits for everyday clothing and specialized applications like sportswear and medical textiles. Moreover, the project emphasizes sustainable processing methods and real-life testing to ensure the textiles perform well under typical use conditions. By addressing these challenges, this research contributes to the growing field of sustainable and multifunctional textiles, aiming to reduce environmental impact while enhancing wearer comfort and fabric performance.

CONCLUSION

In this research, the development of bio-based smart textiles with temperature-adaptive and self-cleaning properties has been explored with a focus on sustainability and multifunctionality. By using eco-friendly materials like polylactic acid (PLA) and innovative microencapsulation techniques for phase change materials, the project successfully demonstrated enhanced thermal regulation that improves wearer comfort in varying temperatures. The application of novel nanoparticle coatings provided effective self-cleaning abilities, reducing the need for frequent washing and contributing to fabric longevity and environmental protection. Importantly, the combination of these two smart functions in a single textile shows promising potential for real-world use in sportswear, healthcare, and eco-conscious fashion. A key achievement of this work is the integration of multiple smart properties using bio-based components and practical processing methods, which sets a foundation for future research and commercialization. This project also highlights the importance of sustainable development in textile technology, addressing

Environmental concerns while meeting modern consumer demands. Overall, this study contributes new knowledge by combining innovative materials and techniques, demonstrating that eco-friendly smart textiles are both achievable and valuable. With further improvements, these textiles can play a vital role in the future of sustainable fashion and smart clothing industries.

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