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Assessing the Chemical, Environmental, and Economic Impacts of Textile Materials, from Dyeing Processes to End-of-Life Management

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Abstract: *Textile and apparel waste have been rapidly increasing over the years, filling up landfills and polluting the environment, and merits an assessment of the environmental and eco-nomic aspects of textile production within the framework of a circular economy. The study employs a mixed-method study to combine literature review with case studies. Interviews with textile industry experts furnish professional observations and practical insights. The research assesses the adoption of nanotechnology and use of biological enzymes in sustainable textile manufacturing and wastewater treatment to clean textile industrial waste in an affordable and eco-friendly way. It observes a reduction in chemical usage and resource waste through waterless dyeing technologies. Despite these im-provements the environmental threats caused by microplastic pollution continue which highlight the need to implement sophisticated detection tools and comprehensive filtration systems. The research notes the technological advancements, the constraints of local infrastructure and the requirement for improved government regulations.*

Keywords: Sustainable Textile, Dyeing Technologies, Wastewater Treatment, Circular Econ-omy, Microplastic Pollution.

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Introduction

The Linear Economy is generally understood to be an economic system in which resources are used to make products that often remain unused and are ultimately disposed of and, up until recently, has dominated almost every industry. However, as humans have become more concerned about the extensive waste generation, resource depletion, and mass pollution it causes, the need for a transition to more sustainable systems became apparent.

Figure 1: A graphical representation of the linear economy's systems

Figure 1 represents the general workflow of the systems in the linear economy. Most products begin with raw materials, which then go into production, becoming the products, which are used and eventually disposed of. With the advent of circular economic policies, we move away from linear economy with an aim to focus on recycling, upcycling, and creating authentic supply chain logistics to deal with massive amounts of carbon emission, microplastics and landfill wastages. There is a need for strict policy regulations and regulatory framework, which focus on zero-waste designs to reduce toxic environmental impacts due to traditional textile disposal methods (Shamsuzzaman et al., 2025). The transition towards more circular policies has shown up in the world of academia where traditional methods of design education training in universities are being replaced by newer, self-sustaining ones. In design education courses in various universities, the use of prototypes and printed materials in teaching has proven to generate large amounts of waste and cause significant environmental damage, contradicting the university's sustainability goals. As a result, students, faculty, and staff have begun an initiative that focuses on continued discussion as to how these unsustainable methods can be replaced by practices that minimize landfill waste, with the aim of incorporating circularity into the core ethos of design training (Lee & Manfredi, 2021).

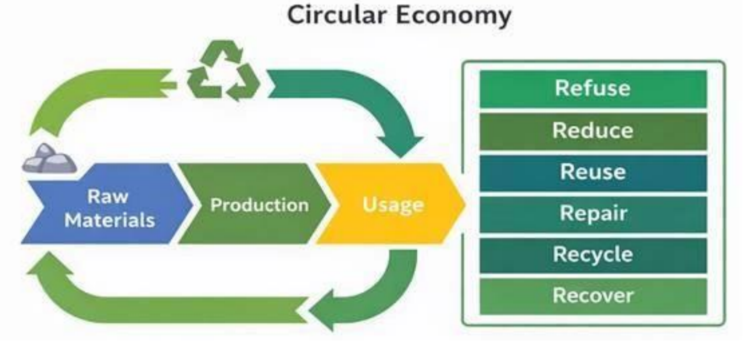

Figure 2: A graphical representation of the circular economy's systems

Figure 2 shows the workflow of the systems in the circular economy. It's the exact same as the linear economy (shown in Figure 1), but instead of being disposed of after usage, the products undergo one of the processes categorized by the 6Rs: Refuse, Reduce, Reuse, Repair, Recycle, and Recover. Once they undergo one or more of these processes, they can then be reused as raw materials, greatly minimizing wastage. Studies have shown that integrating circularity with earlier stages of learning could lead to significant changes in academic behavior. In a study conducted in Kenya, students in rural schools were given free textiles, which significantly reduced absenteeism, especially in those who didn't have textilesprior to the study (Evans & Ngatia, 2020). Even basic household items can be chemically repurposed to form industrial compounds that not only replace but outperform traditionally used materials. When blended with mixed polyolefins, unused surgical masks form rigid compounds that exhibit superior stiffness and strength to standard recycled plastics, and due to their commercial polypropylene-level weathering stability, these compounds can be used for industrial applications (Battegazzore et al., 2021).

The textile used in children's school fabricss and outerwear poses significant health risks, especially in children, and can cause serious developmental issues. This is because of man-made chemicals known as per- and polyfluoroalkyl substances (PFAS) which can be found in a variety of different products. Despite their frequent use, a majority of the specific PFAS chemicals cannot be tracked due to flaws in regulations and difficulty in their detection, therefore, understanding how these compounds enter our environment and are absorbed by the human body can help us understand the health-risks of various consumer goods (Xia et al., 2022). While some international regulations have been imposed, finding ways to adhere to them has caused an issue. Traditional methods of measuring environmental impact are too expensive and complex for startups in new markets to carry out, meaning that to be more sustainable businesses end up suffering. However, some researchers have come up with a strategy incorporating value chain analysis, allowing them to locate specific points in the production process where waste can be reduced. Their research explores how sustainability in the textile industry can be more easily achieved when businesses incorporate more cost-effective circular practices (Edirisinghe et al., 2024). To make textile production processes more sustainable, high importance should be placed on chemical innovation. Advancements such as replacing traditional production methods with green reactions - processes that minimize wastage, prioritize efficiency, and reduce use of toxic materials - are based on scientific principles and can be applied from dyeing techniques to recycling chemicals and water (Choudhury, 2013). The imposition of stricter regulations helps to reduce the harmful effects of toxic metabolites present in natural water systems, but not completely. The reason that these toxic metabolites are present is due to runoff from textile production, where normally harmless substances break down into toxic chemicals. Additionally, these metabolites are present due to the improper disposal of textiles into landfills where 90% of the dyes and chemicals used in them seep into water systems and eventually break down into toxic chemicals. Therefore, it is necessary to adopt circular practices that minimize the quantity of textiles found in landfills and optimize the disposal of waste products from textile production (Nimkar, 2017).

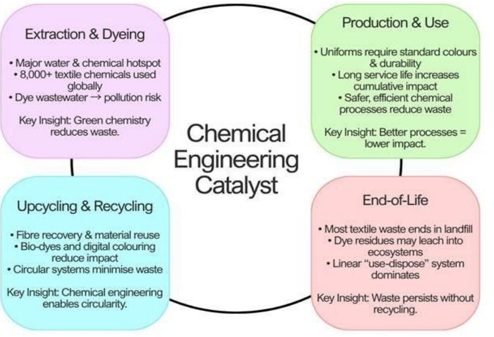

Figure 3: Chemical Engineering Catalysing Circular Upcycling of textile Materials

Figure 3 represents how chemical engineering enables the upcycling of textiles by targeting dyeing and end-of-life hotspots, which are key sources of PFAS release, wastewater pollution, and toxic metabolites. By using eco-friendly dyes, enzymes, and closed-loop water systems, textile manufacturers can significantly minimize their water wastage and consumption. Researchers tested this strategy on cotton and found significant reduction in chemical waste and in water and energy consumption, without any compromises in quality. By using Life Cycle Assessments, the researchers were able to measure the ecological benefits and proved that it was an obvious improvement from the traditional high-impact methods of dyeing and finishing. This new framework helps textile manufacturers transition towards more eco-friendly, cost-effective practices, bringing the textile industry closer to achieving global sustainability goals (Cate, 2025). Another example of upcycling is using oxidative treatment and specialized polymer coating to turn discarded reverse osmosis membranes into high-performance filtration tools. Their ability to separate dyes from salt water, their strong water permeability, and high resistance to building up makes them high-precision filters. This demonstrates the adoption of more circular practices as it reduces the effects of industrial waste and acts as an effective way to prevent water contamination from the dyes (Alkhouzaam & Khraisheh, 2023). To develop circular strategies for waste-management, it is imperative to understand the chemical composition and behavior of the natural and synthetic fibres used in textile production, as each material has a unique chemical treatment, which leads to distinct pollutants that have varying environmental impact. A sustainable cost-effective solution to this problem would be to use microbacteria and enzymes to break down the textile waste. Using biological intervention to purify the water aligns with the UN SDG of clean water, suggesting that, to achieve a more circular economy, the adoption of biotechnology might be an effective way to start (Negi, 2025).

Another way for the textile industry to transition to a more circular economy is by incorporating more sustainable methods of waste disposal. Researchers find that sludge-to-biochar is a very effective process to minimize pollution and can easily be adopted by most businesses as it is cost-effective. This is a good example of showing that adopting circular economy practices not only reduces environmental damage but can also provide cost-effective solutions to manufacturers (Gong et al., 2023).

A study found that for cadmium-telluride solar panels, the best way to dispose them off is by combining reusing and recycling strategies as it minimizes the negative environmental effects caused by toxic leaching of chemicals and also reduces costs to manufacturers as it prevents wastage of tellurium, a rare element needed for future energy production. This method reduces the effect of global warming and resource depletion but implementing it in the entire solar panel industry will be difficult due to infrastructure gaps and high logistics costs. Therefore, incorporating streamlined, integrated recovery systems into the solar industry and others like it will allow them to scale while still working towards the UN SDGs (Ncube et al., 2025).

As the adoption of circular practices is becoming more prevalent, technology is being used to reduce the environmental impact of the textile manufacturing process. One study connects innovations such as waterless dyeing, low-impact dyes, and natural solvent systems to the UN SDGs and measures the effectiveness of each innovation in conserving resources and energy. This shows that there are technological levers that can be used to make the textile industry more circular, but none exist that are specific to textiles yet (Zhang et al., 2022). To achieve a circular economy, circular practices must be incorporated from a managerial perspective. Employees should have an incentive to be more eco-friendly, and researchers found that “Green Human Resource Management” (GHRM) acts as one of those strong incentives. The research shows that performance-based incentives are more effective than other forms of motivation, and that variables such as company size and industry type are important to consider when measuring the success of initiatives (Bindeeba et al., 2025).

Research Objectives

This research’s main objective is to systematically assess sustainable fiber modification, dyeing, and end-of-life management strategies for textile materials through integrated chemical, environmental, and economic analysis. This study attempts to identify significant gaps in micro and nano-plastic mitigation, PFAS management and analytical standardization. It compares conventional and emerging technologies about reduction of pollution, efficiency of resources and scalability while keeping in mind the constraints in regional infrastructures. It seeks to frame sustainability pathways which are actionable and are aligned with the UN SDGs.

This paper is structured as follows: in Section 2 a comprehensive literature review is provided on the chemical composition, the environmental implications, and the economic considerations of materials across their lifecycle. In Section 3 the research questions and hypotheses guiding the study are defined which establish the analytical and conceptual framework. In Section 4 the research framework is outlined, which provides details on the experimental design, techniques used for data collection, and analytical tools employed. In Section 5 the results are discussed to form a cohesive interpretation of the findings, linking chemical, environmental, and economic dimensions. In Section 6 the key findings are summarized, highlighting practical implications for sustainable material management, and suggesting directions for future research.

Literature Review

Researchers have been searching for sustainable treatment technologies to combat the issue of contaminated wastewater caused by the textile industry, the primary source of environmental contamination. One approach to deal with this issue is by applying the circular economy principle to minimize the negative impact on human health and the environment. Overall, the need to use more rigorous assessment for improving the economic and environmental viability of water treatment plants is highlighted by this research (Periyasamy, 2024). Recent studies show that using enzymes to degrade harmful colorants proves to be a cost-effective strategy to tackle the rise in industrial dye pollution. This along with the use of nanoparticles can act as a sustainable and economic alternative for traditional methods of wastewater treatment, though this strategy does require extensive standardization. Nonetheless, scientists believe that by integrating these innovations, a solution to cleaning contaminated water may arise (Alsukaibi, 2022). Bioremedial methods, specifically using microbes and fungi to naturally break down complex organic dyes, is another strategy that scientists believe can be implemented to minimize the negative effects of wastewater contamination. The demand for these more sustainable practices exists because traditional methods to deal with the untreated coloring agents discharged by the textile industry often produce toxic sludge. Scientists recommend using a mix of bioremedial methods and traditional methods to optimally treat industrial waste (Alisha & Kumar, 2024). Another way that wastewater can be treated is using cellulose-based materials, which are able to purify wastewater by trapping and neutralizing pollutants such as organic dyes. However, studies show that while these materials have been engineered to improve their purification capabilities, their effectiveness may vary due to pH levels and exposure duration, which can affect the process's success, demonstrating that technological gaps are yet to be bridged in this method (Rashid et al., 2024). Additionally, cellulose efficiency can be further improved through the use of cationization, which will help it overcome the issue of its dense hydrogen bonds. These bonds cause cellulose to have weak reactivity and low solubility, so by using cationization, cellulose's ability to have ionic interactions with anionic molecules gets enhanced, thus improving its dyeing ability (Negi, 2024).

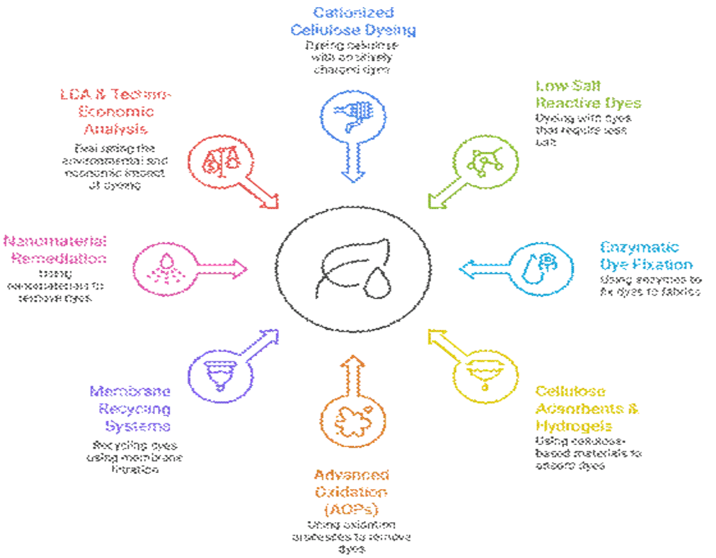

Figure 4: Mindmap of circular dyeing technologies

Figure 4 represents the various methods through which the process of circular dyeing can be achieved, therefore minimizing the contamination of water systems by the textile industry's toxic effluents and pollutants. Water contamination can also be prevented by using more sustainable dyeing technologies. Some alternatives to the traditional methods include supercritical carbon dioxide dyeing, atomic layer deposition, and plasma-assisted dyeing. These technologies employ a closed-loop system, helping minimize wastewater pollution and solvent loss caused by the textile industry. While more sustainable alternatives exist, these dyeing methods are more cost-effective when considering the large volume required for the processes. However, this compromise may no longer be needed as continuous exploration in the field of sustainable fiber technologies may lead to the innovation of sustainable technology that is accessible in large volumes (Negi, 2025b).

To deal with this issue, international organizations like UNEP urge the implementation of green chemistry and circular practices into the textile industry. The synthetic microfibers that are produced from textile manufacturing are the most common man-made pollutants and cause DNA degradation and cell death. These harmful effects occur on a global scale, as these particles contaminate various ecosystems worldwide to rapid industrialization. As a result, global collaboration towards preventing bioaccumulation of microfibers in the food chain is essential to preserving the health of our ecosystems (Yadav et al., 2024). Another issue that requires systematic changes is the issue of microplastic pollution. Many innovations in chemical engineering are implemented to tackle this issue, for example, the use of biochar and functionalized sponges to capture contaminants is a method that is currently in development. Additionally, integrating biodegradable polymers into global textile manufacturing will provide a long-term solution to this issue, and to measure these changes effectively, LCA must be used. However, technology still needs to be able to solve some key research gaps, including improving nano-plastic removal and analytical standardization across the industry (Mohsin & Zaid, 2025). Some countries, such as Rwanda, Japan, and Germany, are already tackling the plastic pollution issue by using effective governance to bring their recycling rates to 41%. Additionally, technological advancements have led to innovations such as chemical recycling and enzymatic procedures, both of which clear plastic with more than 90% efficiency. However, infrastructure also plays an important role in a country/region's ability to implement sustainable practices, for example, in sub-Saharan Africa, it is estimated that only 39-45% of solid waste is treated. As a result of the importance given to infrastructure, a majority of underdeveloped countries struggle to implement the previously mentioned sustainable strategies, thus making global recycling minimal. This can be detrimental as globally nearly 8 billion tons of plastic is discharged into the oceans annually, which then release BPA, dioxins, and phthalates, all of which can lead to severe health disorders (Abahussain et al., 2025).

Solving the microplastic pollution issue is essential to protect human health as after these microplastics break down through photodegradation, physical fragmentation, or microbial biodegradation, they make their way into our drinking water with concentrations of 4.34 particles per liter. Detecting these particles requires state-of-the-art technology like FTIR and Raman Spectroscopy. Integrating these detection processes with advanced wastewater treatment and global regulations will help mitigate microplastic pollution in the long run (Ibrahim et al., 2025). One way the textile and manufacturing industries have begun to introduce sustainable development is through the increased use of wool, a sustainable alternative to synthetic polymers that is being used in insulation, agriculture, smart technology, and advanced biomaterials. The use of wool has been on the rise because industries have begun to adopt more circular strategies, which include using wool as it degrades naturally and doesn't contribute to micro- and nano- pollution. While wool's processing involves harsh chemicals, industries are using more sustainable procedures to ensure wool's viability as a replacement for traditional unsustainable practices (Popescu & Stanescu, 2024). An example of an emerging process that is both sustainable and cost-effective is magnetite-based photocatalysis. This method is very efficient as it curbs the issue of electron-hole recombination, allowing them to successfully react with and neutralize the contaminants. This along with its ability to manage interference from ions and humic acids makes it an efficient alternative to current methods. Implementing this strategy will help in resource recovery, focusing on reusability and regeneration of catalysts. Additionally, with some more innovation towards improving this method's efficiency and aligning it with the UN SDGs may give rise to a successful holistic approach to tackling the water pollution crisis (Ngulube et al.,2024). Using secondary adsorbents is another effective strategy for promoting a circular economy as they can prevent secondary pollution by being repurposed into cost-effective engineered products. These materials can become antimicrobial agents, construction additives, catalysts, and fertilizers. However, the PFAS prove to be a major obstacle with this strategy as the potential presence of these "forever chemicals" is counterintuitive to the aims of using secondary adsorbents, as PFAS are known to pollute air, soil, and water. Therefore, research and management of PFAS-laden adsorbents is necessary for this strategy to be as effective as possible (Nighojkar et al., 2022).

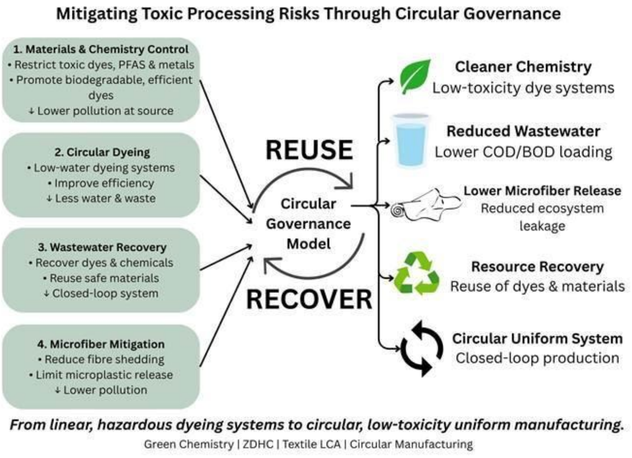

Figure 5: Policy framework for circular dyeing of textile materials

Figure 5 represents possible policy frameworks to implement circular dyeing into the textile industry, showing a multi-level governance model that integrates safer chemistry, circular dyeing technologies, wastewater and resource recovery, and microfiber risk mitigation to reduce chemical toxicity, water use, and life-cycle environmental impacts. China is one of the world's largest textile producers and its textile-dyeing has a significant impact on the environment. Due to scouring and bleaching; dyeing and stenter-finishing; poor wastewater treatment: and incineration, the industry contributes significantly to increased acidification, ozone creation, eutrophication and climate change. Fortunately, using Life Cycle Assessments (LCAs), researchers have identified scopes for mitigating the damage caused by these processes. To improve its environmental profile, researchers suggest that the industry should prioritize resource recycling and using cleaner transport. They also suggest that future efforts consider not just water system impacts, but the normalized toxicity of dyes and managing uncertainties in data (Yuan et al., 2012). The reason that textile production is a significant contributor to pollution is because research into end-of-life sustainability has historically been neglected. However, recent research has led to an innovative strategy that ensures that textile production remains eco-friendly throughout its entire life cycle. The eco-path remediation for flame retardant textiles is a process that applies to an Advanced Oxidation Process (AOP) and is designed to degrade and eliminate pollutants from textiles before they are disposed of. To determine this method's effectiveness, researchers used an LCA and found that this method demonstrated significant reductions in carbon footprint and minimized release of acidifying compounds (Yasin et al., 2017).

The untreated discharge from textile production leads to environmental and health risks including increased eutrophication caused by dyes, severe liver and kidney damage, and resource depletion due to contamination. Therefore, finding an effective method to mitigate or prevent these effects is imperative. While many of the traditional methods work, they are unsustainable in the long term due to high energy requirements, high chemical costs, and unfavorable byproducts, meaning that for most countries, incorporating sustainable practices is not feasible. However, anaerobic digestion is one method that can overcome these hurdles. Anaerobic digestion is a treatment method that overcomes the negative economic impacts associated with traditional methods, as it consumes fewer chemicals and recovers energy. An added advantage is that the cost of this process can be offset by revenue generated from the sale of the byproducts (Tumanyisibwe et al., 2024).

Table I. Dyeing processes to end-of-life management

References	**Key Findings**	**AI Tools**	**Policy Recommendatio n s**	**Research Gap**
Green Chemistry and the Textile Industry (2013)	Green chemistry reduces textile pollution	None	Adopt green chemistry principles	Lacks empirical implementation data
Life-cycle assessment of continuous pad-dyeing (2013)	Dyeing stages dominate environmenta l impacts	GaBi LCA softwa re	Target high-impact dyeing processes	Limited toxicity normalization
PFAS in North American School textiles (2022)	Textiles significant PFAS exposure source	PIGE, TOP assay	Regulate PFAS in textiles	Long-term exposure outcomes unknown
Sustainable Chemistry in Developing World (2017)	Sustainable chemistry essential for textiles	None	Enforce ZDHC, cleaner production	Lacks quantitative impact metrics
Toxic threats from plastic waste (2025)	Plastic toxins threaten human health	None	EPR, plastic bans	Combined toxicity effects unclear

Promoting recycling, reducing and reusing in design education (2021)	Design schools catalyze recycling behaviors	None	Embed circular practices in education	Behavioral impact not quantitatively measured
Anaerobic digestion of dye wastewater with biomass (2024)	Co-digestion improves biogas, resource recovery	None	Adopt wastewater-to-ener gy systems	Economic scalability insufficiently evaluated
Sustainable conversion of PFAS-saturated adsorbents (2022)	Recovered adsorbents retain PFAS risks	None	Regulate reuse of PFAS materials	PFAS fate in reused materials unclear

After a methodical review of prior literature, a review matrix (Table 1) was developed integrating available research on dyeing technologies, textile chemistry, hazardous substances, and circular sustainability strategies. Key gaps were observed, particularly inadequate knowledge of the impact of chemical reuse and substitution in textile systems on health and environment, lack of empirical validation for circular and green chemistry mediations at industrial level, and limited integration of life-cycle assessment with regards to toxicological impacts and human exposure.

Research Questions

1. In what way do fibre modification and the use of alternative dyeing technologies impact the overall life cycle environmental and economic performance of textile materials?
2. How well do emerging treatment solutions (e.g., new fibres) for PFAS contaminations and micro- and nano-plastics compare to traditional methods?
3. How do regional infrastructure limitations hinder the applicability and effectiveness of sustainable textile approaches related to the UN Sustainable Development Goals (SDGs)?

Research Hypotheses

1. Hypothesis 1: Cationizing cellulose fibres leads to improved dyeing performance from an efficiency perspective and a decreased environmental load than the use of cellulose fibres that have not been cationized.

2. Hypothesis 2: The application of new treatment technologies including anaerobic digestion and magnetite-based photocatalysis have a lower long term environmental impact and cost compared to traditional methods.
3. Hypothesis 3: The use of adaptive sustainability strategies in developing an infrastructure provides greater benefit than deploying uniformed technologies in regions with different waste handling capabilities.

Research Methodology

This study uses a mixed-methods research design based on a systematic and qualitative fusion of peer-reviewed literature sourced entirely from high-quality databases, including Scopus, Web of Science, IEEE Xplore, and ABDC-ranked journals. For Research Question 1, a. PRISMA-guided systematic review protocol is utilised to identify, vet, and analyse Life-Cycle Assessment (LCA), Techno-Economic Analysis (TEA), and comparative performance studies evaluating fibre modification and alternative dyeing technologies. For Research Questions 2 and 3 a qualitative research methodology is employed based on thematic content analysis of experimental studies, policy reports, and industrial case studies. It focuses on PFAS remediation, micro and nano-plastic mitigation, and infrastructure-dependent sustainability outcomes. Cross-study triangulation is applied to ensure consistency, while methodological quality and relevance are assessed using standardized inclusion criteria. This approach enables an integrated evaluation of environmental, economic, and infrastructural dimensions of sustainable material systems across various regional contexts.

RQ 1: In what way do fiber modification and the use of alternative dyeing technologies impact on the overall life cycle environmental and economic performance of textile materials?

PRISMA Modelling

This study investigates sustainable advancements in the textile industry. It focuses on technical textiles used in fabrics and examines the impacts of innovative dyeing and fiber modification techniques. The study employs a PRISMA-guided review protocol which provides a structure to combine complex data and helps ensure the accuracy and credibility of the findings. As literature covers different disciplines, from ecology to economics, this standardized approach is essential. The use of this rigorous framework helps eliminate subjective bias while synthesizing various industry and academic sources, ultimately providing a valid, evidence-based overview of sustainable innovation within the global textile life cycle (Moher et al., 2009) (Page et al., 2020). The PRISMA 2020 framework was selected for this research as it follows internationally recognized standards for transparency and consistency in the research process, which is enforced by the strict guidelines for data collection, ensuring every stage of evidence screening is documented clearly. Using this structure, researchers can integrate a wide range of fields into a single cohesive study. Ultimately, this helps authors assess potential biases and evaluate the overall performance of manufacturing methods, ensuring reproducibility and accuracy in the findings regarding textile syntheses. The PRISMA 2020 framework for this review follows the following sequential phases: Identification, Screening, Eligibility, and Inclusion. Each of these phases is methodological rigor, ensured using a strict decision criterion applied by two independent reviewers. Additionally, by using the PICO framework as a research methodology, PRISMA helps researchers understand and strategize the research question.

PICO Framework

PICO Element	Definition	Application to This Study
Population (P)	Materials and population investigated for paper	Fabric materials and textiles used in institutional, military, occupational, and healthcare settings, comprising natural fibres (cotton, wool), synthetic fibres (polyester, nylon), and blended fabrics
Intervention (I)	The technological advancements or changes being examined	Fibre modification technologies (surface treatment, chemical modification, bio-based fibre substitution) and alternative dyeing technologies (waterless dyeing, natural dyeing, digital printing, CO2 dyeing, plasma treatment)
Comparison (C)	The standard or comparator against which the effectiveness of the intervention is being assessed	Traditional fibre processing and standard aqueous dyeing methods (reactive dyeing, vat dyeing, disperse dyeing) as benchmark comparators for environmental and economic performance
Outcome (O)	The measured relevant impacts	Environmental performance metrics: Global Warming Potential (GWP), water consumption, energy use, chemical toxicity, waste generation; Economic performance metrics: production cost, capital

		investment, processing efficiency, cost per unit output

The criteria for inclusion and exclusion used to create the PICO framework is:

Inclusion Criteria

For a study to be included it must be published in peer-reviewed journals or credible grey literature sources between January 2000 and December 2024. Additionally, they are required to use reproducible methodological approaches to produce qualitative or quantitative data in English about the economic and environmental performance of fibre or dyeing processes, focusing on textiles, workwear, or institutional apparel contexts

Exclusion Criteria

Studies will be excluded if they are identical publications describing the same dataset; are editorials, opinion articles, or reviews that lack original data; or if they lack sufficient methodological detail for an effective analysis. Additionally, if a study focuses on fashion or luxury apparel fibres that have no application to textiles; only reports data at a molecular level with no mention of industrial scalability; or doesn't provide primary empirical data or quantitative/qualitative data regarding economic or environmental impact it is excluded.

A comprehensive multi-database search strategy was employed to maximize retrieval of relevant evidence. The database was searched based on the following criteria:

1. Different repositories like Scopus, Web of Science, Google Scholar, Science Direct, and Textile Technology Index
2. Boolean Search String (eg. "fiber modification" OR "fiber modification" OR "textile modification" OR "surface treatment" OR "bio-based fiber" OR "natural fiber" OR "sustainable textile") 3. The paper selected are from 2017-2025

PRISMA Flow Diagram

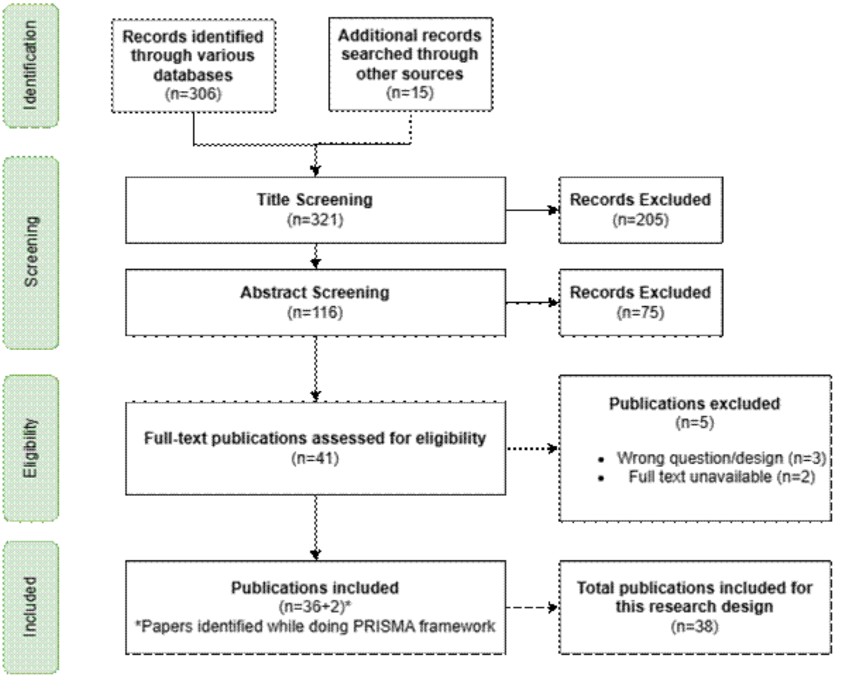

Figure 6: Flow chart representing the step-by-step methodology of the PRISMA Framework

The first step was Identification. Here researchers executed targeted search strings across various digital repositories to collect relevant academic records. After the information was collected, it was imported into a centralized management system to simplify the handling of large datasets. Subsequently, under human oversight and using software-tools, the information was subjected to a thorough deduplication process to ensure the database remained clean and unique. This method minimizes errors in data and provides a consistent structure for scholarly documentation.

The second step was screening. Here the title and abstract of the 321 records that were received from the identification phase were examined thoroughly, and based on their relevance to the topic, along with various other factors, 280 records were excluded.

The third step was Eligibility, where full texts of the 41 records that pass the screening were retrieved and assessed by two independent reviewers against the eligibility criteria. Reasons for exclusion were documented for each excluded record, as required by PRISMA 2020 reporting standards.

The fourth step is Inclusion. Here, after passing the full-text eligibility assessment, the 38 publications were collected to form the final study set and were then divided into two synthesis streams: Narrative synthesis and selective meta-analysis.

Results and discussion: RQ1

Table III. 5 Key elements of RQ1

Element	How PRISMA Proves It
Fibre modification	~15 studies specifically on this, identified through keyword search
Alternative dyeing technologies	~17 studies on waterless/CO2/natural/digital dyeing, isolated through PICO framework.
Environmental performance	Quantified through LCA metrics (GWP, water, energy) extracted from all studies and meta-analysis is done.
Economic performance	Cost data was analysed through~6 studies with narrative thematic analysis
Across the life cycle	System boundary documentation is used for every life cycle stage.

Dimension 1: Environmental Performance — Fibre Modification

Table IV. Representation of the findings and expected conclusions from studies about fibre modification's effect on environmental performance

Finding Type	Expected Evidence-Based Conclusion
Direction of effect	Synthesis of ~75 LCA studies will establish the effect fibre modification technologies have on environmental performance metrics (GWP, water, energy) relative to conventional fibres
Magnitude of effect	Meta-analysis will quantify the mean percentage reduction in GWP and water consumption achievable through specific fibre modification technologies, with confidence intervals reflecting study variability
Life cycle stage specificity	Narrative synthesis will identify which life-cycle stages (fibre production, dyeing/finishing, use, end-of-life) benefit most from fibre modification, directly addressing the 'across their life cycle' element of the research question

Technology comparison	Subgroup analysis will rank modification technologies (bio-based substitution vs. surface treatment vs. chemical modification) by environmental performance improvement, providing actionable guidance for textile manufacturers

Dimension 2: Environmental Performance — Alternative Dyeing Technologies

Table V. Representation of the findings and expected conclusions from studies about alternative dyeing technologies' effect on environmental performance

Finding Type	Expected Evidence-Based Conclusion
Water reduction evidence	Meta-analysis of waterless dyeing studies (CO_2, digital, plasma) will produce a collective estimate of reduction in water consumption vs. conventional aqueous dyeing, expressed in litres/kg with 95% CI
GWP comparison	Forest plots will display individual study GWP estimates for each alternative dyeing category against conventional dyeing baseline, showing consistency or variability of environmental benefit
Wastewater elimination	Evidence synthesis will confirm which technologies (particularly supercritical CO_2 dyeing) completely eliminate processed wastewater, addressing a burden of conventional dyeing
Energy trade-offs	Narrative synthesis will document cases where alternative dyeing reduces water use but increases energy consumption, revealing the required environmental trade-offsl for life cycle decision-making

Dimension 3 & 4: Economic Performance

Table VI. Representation of the findings and expected conclusions from studies related to both methods' influence on economic performance

Finding Type	Expected Evidence-Based Conclusion
Cost competitiveness	Techno-economic analysis will determine the specific output levels at which innovative dyeing processes reach the same price point as traditional techniques, which is vital data for those managing textile acquisition
Capital investment burden	Economic narrative synthesis will quantify the upfront investment required to adopt circular technologies and methodologies relative to long-term operational cost savings, providing payback period evidence
Combined environmental-economic trade-off	Integration of environmental and economic synthesis will identify technologies that achieve both environmental improvement and economic viability simultaneously — the ideal scenario for sustainable textile production
Technology readiness	Evidence synthesis will classify each technology by industrial maturity (laboratory, pilot, commercial scale), informing the viability of research findings to actual textile manufacturing contexts

The PRISMA 2020 framework proves the research question - How do fibre modification and alternative dyeing technologies influence the environmental and economic performance of textile materials across their life cycle - not through a single study or experiment, but through the rigorous, systematic, and transparent synthesis of the global body of evidence. Each of the steps mentioned in the Research Methodology document plays an invaluable role in building this proof.

RQ 2: How well do emerging treatment solutions (e.g., new fibres) for PFAS contaminations and micro- and nano-plastics compare to traditional methods?

Case Study 1:
Unlike conventional methods, emerging treatment technologies such as magnetite-based photocatalysis and anaerobic digestion seem to have lower long-term environmental and economic costs. While the traditional method of coagulation-flocculation results in excess

sludge and high chemical costs, magnetite-based photocatalysis's use of reactive oxygen species generation along with the presence of magnetically recoverable Fe_3O_4 catalysts minimizes wastage and facilitates cost-effective and efficient breakdown of dyes, thus making it much more sustainable and economically viable for large-scale processes compared to traditional methods of treatment (Ngulube et al., 2024b). Additionally, the use of anaerobic digestion provides an opportunity to not only minimize textile wastage but convert it into renewable energy. This process minimizes greenhouse gas emission by converting harmful effluents into valuable power sources which can either be used by the producer or sold, thus acting as a revenue source. Anaerobic digestion also minimizes costs as by processing the toxic sludge without oxygen, biogas is released and energy requirements are lowered. This process can be enhanced by nanostructured additives, which can increase its financial viability (Sangubotla et al., 2025b). While these methods require significant financial investment initially, they yield various long-term benefits. Through energy recovery, decreased chemical usage, and focus on efficient resource use, photocatalysis and anaerobic digestion can greatly minimize costs and environmental impact. These processes also align with various sustainability goals by protecting aquatic ecosystems and reducing industrial waste. While obstacles regarding infrastructure and scalability are present, integrating the strategic systems presented by these processes is essential for achieving a circular economy (Ngulube et al., 2024d).

RQ 3: How do regional infrastructure limitations hinder the applicability and effectiveness of sustainable textile approaches related to the UN Sustainable Development Goals (SDGs)?

Case Study 2:

While all these strategies seem effective in theory, their practicality is another issue. Studies have found that geographic disparities in infrastructure significantly affect the environmental impact of materials across their functional lifespan. For example, wealthier nations can adopt advanced circular systems much easier than developing countries, due to their access to funding. This means that the success of implementing these circular strategies and transitioning to more green production is determined by resource availability and infrastructure, creating a global divide where some countries are able to easily transition to and maintain a circular economy and others aren’t (Haq, F. et al., 2024). Consequently, aligning technological innovation with the specific infrastructures of the region by offering decentralized treatment methods and low-energy technologies is critical to achieve the UN SDGs. Ultimately, collaborative global effort and dedicated investment are essential for integrating sustainable and circular practices into the global textile industry (Alaghemandi, 2024).

Figure 7: Life-cycle stages and their descriptions

Figure 7 represents the life-cycle stages of textile production and provides a description for each stage, including its key focus, aligned UN SDG, and impacts on society. This provides an opportunity to analyze the various aspects of textile production and thereafter plan an appropriate approach to adopting more circular practices based on the key focuses, impacts, and respective SDGs of each stage.

Results and Discussions

There is prevalence of PFAS in textile products for children, particularly those that are marketed as “stain-resistant” or “waterproof.” These expose millions of children to harmful chemicals and are also a source of PFAS release to the environment (Xia, C. et al. 2022). This study combines chemical, environmental and economic aspects into a unified life-cycle perspective. The PRISMA-based review indicates that requirement for auxiliary chemicals can be reduced, and wastewater toxicity can be lowered by fiber modification techniques, especially the cationization of cellulose which substantially improves dye affinity. This is supported by case study analysis which reveals the effectiveness of alternative dyeing technologies in drastically cutting water and energy usage. There is an economic benefit from the adoption of anaerobic digestion as a wastewater treatment method because it reduces chemical input costs and aids energy recovery, helping make the process more efficient. Moreover, the use of secondary adsorbents enables waste valorization by converting pollutants into reusable industrial inputs. However, the success of such methodologies is affected by the ongoing challenge of safely managing and reusing PFAS-laden materials. As evidenced by research findings, textile waste recycling faces multiple challenges (M. Shamsuzzaman et al. 2025). A coordinated action is required across technology usage, policy, supply chain management, and consumer engagement

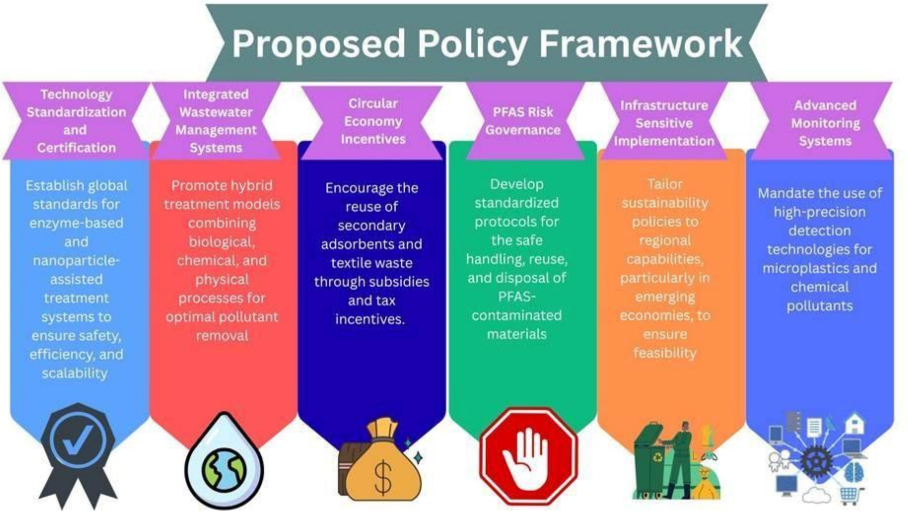

Figure 8: Proposed Policy Framework

This study contributes toward developing a new combined framework connecting technology with policy and infrastructure considerations. In their interviews, sustainability experts and textile professionals underscore the importance of hybrid treatment systems that combine biological and conventional methods to boost outcomes. Experts stress the need for standardization to ensure industrial scalability and regulatory compliance in emerging technologies, particularly enzyme-based and nanoparticle-driven treatments. The use of advanced dyeing and treatment technologies shows substantial environmental benefits. However, implementing these measures has been often restricted, particularly in developing regions, owing to the problems of cost, technical expertise, and policy support. The study finds significant gaps in aligning technological advancements with regional infrastructure capabilities. This highlights the need for progressive governance frameworks that promote sustainable practices while adapting to regional differences.

Conclusion

This study incorporates literature review, analysis of case studies and interviews with professionals to get an understanding of the chemical, environmental and economic impact of textile materials. It notes that innovation and a scientific approach are contributing to economic efficiency and in making the textile industry more environmentally friendly. It is critical to address existing gaps and shortfalls through a combination of suitable policy changes, use of the latest technology and infrastructure development. These have to be backed by robust regulatory measures to tackle the continuing hazards of microplastic pollution and PFAS contamination. The study proposes a framework involving the industry stake holders, policy makers and researchers to coordinate their efforts to be in alignment with circular economy principles.

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