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ECOSPIN: FROM FACTORY SCRAPS TO CIRCULAR FASHION

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Abstract

The garment industry generates substantial volumes of freshly cut fabric scraps during pattern planning and cutting, much of which is discarded or used in low-value applications. To address this challenge, a modular and computerized recycling system has been conceptualized to transform fabric cutting waste into high-quality, spinable yarns. The design features four dedicated chambers for cotton/viscose, polyester/synthetics, nylon, and wool/silk fibers, each applying fiber-specific chemical dissolution or depolymerization to generate polymer solutions. These solutions are purified and extruded through controlled wet or melt spinning units, depending on the fiber type, to produce continuous filaments comparable to virgin quality without the need for blending. Inline sensors and a PLC-based control system continuously monitor chemical concentrations, polymer dope parameters, and spinning conditions to ensure safe operation, consistent performance, and product quality. The resulting yarns retain key fiber properties, making them suitable for apparel applications such as jerseys, jeans, jerkins, and other premium textiles, as well as upholstery and technical fabrics. By combining solvent recovery, chemical safety, and advanced process automation, the system provides a sustainable closed-loop pathway for fabric scraps. This approach minimizes landfill waste, reduces reliance on virgin fiber production, and supports the growing demand for eco-labeled fabrics, ultimately advancing the circular economy within the textile sector

Keywords**:** *Circular economy, Cutting waste recycling, Fiber-specific chemical dissolution, Sustainable textiles, Wet/melt spinning*

1. INTRODUCTION

[10] The fashion sector is growing very rapidly, at the same time creating an environmental problem, which is producing more textile waste. Although both natural and synthetic fibers break down slowly in landfills, they release hazardous chemicals into the soil and groundwater.[8] Large-scale incineration also makes the air more polluted. [1] Hence, there is a need for technologically advanced, closed-loop recycling systems that can recover high-grade fibers, instead of manufacturing downcycled materials, as the capacity, quality, and economic sustainability of current recycling procedures are still limited.

This problem is addressed by the EcoSpin system, it is a multifunctional fiber-regeneration device that combines yarn spinning, solvent recovery, chemical recycling, and polymer resynthesis into an integrated system. Each of the four main types of textile materials—cellulosic fibers (cotton, viscose), polyester (PET), nylon (polyamides), and protein fibers (wool, silk)—undergoes a particular dissolution or depolymerization technique which is appropriate to its molecular structure. The system is meant to be a comprehensive solution for decentralized textile recycling by designing all four chambers to operate independently while integrating through centralized purification and spinning units.

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The objective is to create a unified methodology that enables the production of regenerated yarns that are on par with virgin fibers by bridging industrial chemical-engineering principles, polymer science, and textile manufacturing processes.

2. REVIEW OF LITERATURE / BACKGROUND

Global Textile Waste and Limitations of Existing Recycling Approaches

[10] Over 90 million tons of textile waste are produced each year globally, with polyester and cotton making the largest contributions. [9]The most popular technique, mechanical recycling, frequently results in degraded fibers because of contamination and polymer chain scission. [2],[4] There are conventional chemical recycling technologies, but they are usually capital-intensive, mono-material, and require sizable industrial infrastructures. Problems like low solvent recovery efficiencies, low depolymerization yields, colorant interference, and expensive purification steps are highlighted in the literature.

Cellulosic Fiber Dissolution Systems

[1] The recycling of cellulosic fibers has depended on the viscose process, which involves steeping cellulose in sodium hydroxide and introducing carbon disulfide (CS_2) to produce cellulose xanthate. Although this method has been employed in industry for a long period, it is associated with the release of harmful sulfur emissions, posing significant environmental concerns. Modern research is focused on developing more sustainable alternatives. [8]The Lyocell process, which utilizes N-methylmorpholine-N-oxide (NMMO), allows for the dissolution of cellulose without prior derivatization, promoting a closed-loop system that achieves over 99% solvent recovery. [3]Additionally, ionic liquids (ILs), including [Bmim]Cl and other imidazolium-based salts, have been identified as effective cellulose solvents due to their capability to disrupt hydrogen-bond networks. [5]Current literature indicates that ILs can dissolve cellulose, wool, silk, and select synthetic materials, although their elevated costs and purification issues persist.

Polyester (PET) Chemical Recycling Technologies

Polyethylene terephthalate (PET), which is the most widely used polyester, has been the focus of a lot of research on chemical recycling. [9] The glycolysis process, which involves ethylene glycol (EG) and metal catalysts such as zinc acetate to break the ester bonds, is still considered the most practical option in the industry. This method produces bis(hydroxyethyl) terephthalate (BHET), [4] a monomer that can be turned back into PET that's very close to new. Studies on methanolysis and hydrolysis show that while they can produce high-purity yields, they require more pressure and energy. Literature shows that glycolysis is the best balance between cost, energy, and output quality.

Nylon Depolymerization

[6],[9] Studies on recycling nylon show that nylon 6 can be broken down into ε-caprolactam through processes like hydrolysis, alcoholysis, or using catalysts. There are already some industrial setups that can recover caprolactam at a level of purity good enough to reuse in making new polymers. But on the other hand, nylon 6,6 is a bit tougher to break down. It requires critical conditions, such as supercritical water or strong acid catalysts, because of its strong polymer structure. Research says that this process can create salt and some corrosive byproducts, which might increase purification costs.

Keratin and Silk Dissolution

Research into recycling wool and silk is still in its early stages.[7] Keratin and fibroin proteins are pretty tough because of their strong disulfide and hydrogen bonds, so they don't dissolve easily in regular solvents. [3],[5] But recent studies have found that using thiol-based reducing agents, along with $CaCl_2$/ethanol/water combinations and ionic liquids, can actually do the trick and break down these

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protein fibers. These methods help keep the molecular weight intact, which is important for regenerating the fibers. Also, it’s noted in various studies that often, to enhance the strength when spinning, these protein fibers need to be mixed with polymers like PVA.

Gap in Literature

While extensive work has been conducted on individual recycling methods, no system integrates multi-polymer dissolution, purification, polymer re-synthesis, solvent recovery, and yarn spinning into a compact unit. EcoSpin aims to fill this gap by creating a modular, automated, scalable platform.

3. METHODOLOGY

Overall System Design

EcoSpin consists of four dedicated chemical-processing chambers connected to a shared purification, solvent recovery, re-polymerization, and spinning module. Each chamber uses chemical systems tailored to the polymer type.

Fiber Classification and Pre-Treatment

The first stage involves the classification and preparation of textile waste. Garments are sorted into cellulosic, polyester, nylon, and protein-based categories using visual identification, burn tests, spectral sensors, or AI-enabled sorting systems. Fabrics undergo pre-washing using surfactants and alkaline solutions to remove dirt, oils, lanolin (in wool), and water-soluble dyes. For heavily dyed garments, mild oxidative treatments can be applied to prevent dye interference in subsequent chemical reactions.

Chamber-Specific Chemical Processes

Chamber A: Cellulosic Fibers (Cotton, Viscose, Regenerated Cellulose):

[1] Inside the cellulosic chamber, there are three main chemical systems at play: the NMMO dissolution method (also known as the Lyocell process), ionic-liquid dissolution, and the viscose method. With NMMO, cellulose fibers get heated along with NMMO monohydrate. This process breaks down hydrogen bonds and creates what we call a cellulose dope.

NMMO (Lyocell) — physical dissolution (no chemical conversion):

$$\boxed{\mathrm{R{-}OH+NMMO\ (solvent)} \rightleftharpoons \mathrm{[ROH\cdot\ NMMO]\ (solvated\ cellulose\ dope)}}$$

[3],[5] Ionic liquids work in a similar way, but they need to be really dry and kept at specific temperatures.

$$\boxed{\mathrm{R{-}OH+[IL]} \rightleftharpoons \mathrm{[R\text{-}OH\cdot\ IL]\ (solvated\ cellulose\ dope)}}$$

[1] Then, the viscose process involves steeping cellulose in sodium hydroxide, turning it into alkali cellulose. Then, it reacts with carbon disulfide to make cellulose xanthate, which is dissolved in a diluted NaOH solution and finally regenerated through an acid bath.

Step 1 — Mercerization/formation of alkali cellulose (activation):

$$\boxed{\mathrm{R{-}OH + NaOH \longrightarrow R{-}O\ Na + H2O}}\ \text{(alkali cellulose; alkali swells and activates the cellulose chains)}$$

Step 2 — Xanthation (derivatization with carbon disulfide):

$$\boxed{\mathrm{R{-}O\ Na + CS2 \longrightarrow R{-}O{-}C({=}S)SNa}}\ \text{(cellulose xanthate; this is the soluble derivative)}$$

Step 3 — Dissolution to form a viscose solution:

cellulose xanthate (solid) + dilute NaOH (aq) ⟶viscose (soln. of xanthate)

Step 4 — Regeneration (acid coagulation/acid hydrolysis) to recover cellulose:

R−O−C(=S)SNa+ H+ H2O ⟶R−OH + (sulfur-containing by-products, e.g. CS2, sulfides, sulfates)

Chamber B: Polyester (PET):

[6] The polyester chamber mainly uses glycolysis, where PET fibers come into contact with ethylene glycol, and catalysts like zinc or manganese acetate help the process along. This transesterification breaks down the polymer chains into BHET monomers. After that, BHET is cooled, crystallized, filtered, washed, and then repolymerized in a melt-polycondensation unit to create PET resin that's ready for melt spinning. For specific waste materials that need a tougher depolymerization, methanolysis and hydrolysis can also be used.

[−OC−Ph−CO−O−CH2−CH2−] n
[Ph = phenylene ring (terephthalate unit)]

Step 1 — Glycolysis (transesterification)

[−OC−Ph−CO−O−CH2CH2−]+HOCH2CH2OH⟶HOCH2CH2O−CO−Ph−COOCH2CH2OH

[BHET = bis(2-hydroxyethyl) terephthalate (HO–CH2 CH2–O–CO–Ph–CO–O–CH2 CH2–OH)]

Step 2 — Methanolysis (alcoholysis)

PET+2 CH3OH⟶DMT+HOCH2 CH2OH

[DMT = dimethyl terephthalate (Ph(CO2CH3)2)]

Step 3 — Hydrolysis

PET+H2O⟶HO−Ph−COOH (TPA)+HOCH2CH2OH

[TPA = terephthalic acid (HOOC–Ph–COOH)]

Chamber C: Nylon (Polyamide) Fibers:

The nylon chamber involves hydrolysis, alcoholysis, or catalytic depolymerization. Nylon 6 is heated in the presence of water or alcohols, often with catalysts, yielding ε-caprolactam, which is purified by distillation.

Nylon 6:

–CO–NH– + H_2O → ε-caprolactam (with catalyst + heat)

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Nylon 6,6 may require supercritical water to break its strong amide bonds, yielding adipic acid and hexamethylenediamine. These monomers can be re-polymerized using standard polycondensation methods.

Nylon 6,6:

Breaks into adipic acid + hexamethylenediamine.

Chamber D: Protein Fibers (Wool, Silk):

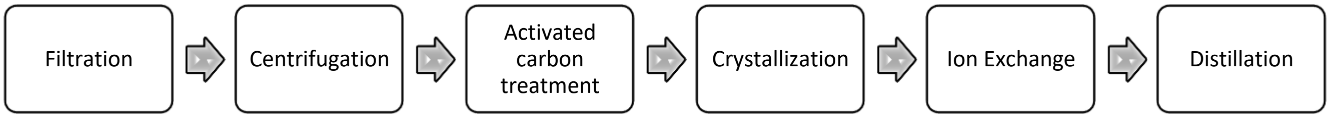
[7] In the fourth chamber, they process protein fibers like wool and silk using a mix of chemicals, including thioglycolic acid, sodium sulfide, DTT, and $CaCl_2$, combined with ethanol and water, or even ionic liquids. These reducing agents help break the disulfide bonds found in keratin, and the $CaCl_2$ solvents mess with the ionic and hydrogen bonds. All this results in a protein-rich dope that can either be wet-spun into regenerated fibers or mixed with other polymers to enhance their mechanical properties.

Disulfide-reduction (keratin solubilization):

$$\boxed{R{-}S{-}S{-}R + 2\ HS{-}R' \rightarrow 2\ R{-}SH + R'{-}S{-}S{-}R'}$$

Purification Unit

Cleaning up the fibers is really important for keeping their quality. We get rid of solid contaminants with filtration, and when it comes to spinning dopes, we clear them up using centrifugation. To tackle dyes and other organic impurities, we either use activated carbon treatment or membrane filtration. PET monomers need to be crystallized and washed, while nylon monomers go through ion-exchange purification to take out salts. And for solvents like NMMO, ionic liquids, ethylene glycol, and methanol, we use vacuum distillation to recover and recycle them back into the system.



Spinning Module

The last step is spinning. For cellulose and protein solutions, wet spinning is the method of choice, where the mixture is pushed into a coagulation bath. On the other hand, dry-jet wet spinning works better for NMMO-derived solutions since it leads to stronger fibers. When it comes to repolymerized PET and nylon, melt spinning is the way to go, where molten polymer gets extruded through spinnerets to create filaments. After that, we have post-treatment processes like washing, drying, drawing, and heat-setting, all of which help improve the strength, evenness, and crystallinity of the fibers.

Safety and Sensors

The system is equipped with high-tech sensors and controls to keep everything safe. Gas detectors check for CS_2 and H_2S, while oxygen sensors help stop NMMO from breaking down due to heat. There are also pH and conductivity sensors that monitor the reaction conditions. Inline FTIR probes, viscometers, and refractive index meters make sure the dope stays consistent and that the monomer is pure. Also, a PLC-based automation system handles temperature and pressure to ensure everything runs smoothly and safely.

4. RESULTS AND DISCUSSION

Expected Performance of Each Chamber

Cellulosic chamber:

In the cellulosic chamber, [8] NMMO dissolves cellulose at controlled temperatures, resulting in a uniform solution.[3],[5] Ionic liquids dissolve and create fibers with impressive mechanical properties, but they do need advanced recovery systems to manage them properly. On the other hand, the viscose process is effective but not the best choice because of the toxicity of CS_2. Luckily, EcoSpin's closed-loop design helps minimize emissions.

Polyester chamber:

In the polyester chamber,[2],[4] glycolysis gets PET reacting with ethylene glycol to produce BHET, with conversion rates between 80% and 95%. The purity of BHET is often over 98%, allowing us to create high-strength regenerated polyester through melt spinning. There's a lot of research backing up glycolysis for textile-grade PET since it can handle a mix of colors and blended materials quite well.

Nylon chamber:

[6] The nylon chamber experiments show that you can recover over 90% of caprolactam if you hit the right conditions. Also, when you re-polymerize nylon, it keeps its strong tensile properties, which makes it great for high-performance fabrics. Now, depolymerizing nylon 6,6 is a bit tougher, but it's doable with supercritical water. The regenerated monomers can then be re-polymerized through condensation reactions to create nylon granules along with virgin-grade materials.

Protein fiber chamber:

[7] As for the protein fiber chamber, the recycling is done by using solvents like thioglycolic acid and $CaCl_2$ effectively breaks down the keratin structure into a spinnable solution. While regenerated keratin fibers may be a bit weaker on their own, mixing them with other polymers can really boost their strength. Also, these recycling systems can produce biodegradable fibers, which is a bonus for the environment compared to synthetic options.

Comparative Assessment of Chemical Routes

Table I: Comparative Assessment of Chemical Routes

Fiber Type	Preferred Chemical Route	Advantages	Challenges
Cellulose	NMMO / ILs	High-strength fibers; recyclable solvents	Thermal sensitivity (NMMO); IL cost
PET	Glycolysis	High monomer recovery; scalable	Requires purification
Nylon	Depolymerization	Regains monomers	High temperature/pressure
Wool/Silk	$CaCl_2$/IL systems	Maintains chain integrity	Slow dissolution; cost

Engineering Analysis of the Integrated System

EcoSpin's modular setup provides effective heating, cooling, and solvent separation thanks to its design. The stainless steel reactors are great because they resist corrosion, and having PLC-driven automation helps keep everything safe during operations. Plus, the solvent-recovery loops cut down on operating costs significantly and make it possible to run continuously. The spinning modules also ensure that the

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filament quality stays consistent, showing that even compact chemical recycling systems can deliver top-notch results when designed well.

5. CONCLUSION AND FUTURE SCOPE

Conclusion

In conclusion, the EcoSpin idea offers a solid way to achieve decentralized textile circularity. It does this by bringing together methods like multi-material chemical recycling, solvent recovery, and fiber regeneration. The four-chamber setup creates specific paths for dissolving materials, using proven chemical processes. This means we can break down and purify cellulose, polyester, nylon, and protein fibers individually, then reconstruct and spin them back into usable yarns.

Also, by adding solvent-recovery loops, we boost sustainability and cut down on both environmental impact and costs. If we optimize things like temperature, catalysts, reactor materials, and purification methods, the fibers we get can be as strong and high-quality as virgin ones.

Future Scope

Looking ahead, EcoSpin has some exciting possibilities. There's room to include AI-driven sorting systems for better material identification, use enzymatic recycling to cut back on chemicals, and develop technologies for dissolving mixed fabrics that are not easy to recycle. Future improvements might also involve integrating renewable energy, refining solvent-engineering techniques, and using digital-twin simulations to enhance efficiency. If we can roll out EcoSpin in communities or industries, it could really help reduce textile waste, diminish pollution, and promote a circular fashion economy.

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