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Challenges of polyester-cotton textiles co-fractionation

Abstract

Waste problem on plastic relates to micro plastic issue and synthetic textile fibers pronounce part of the problem. Inherently the problems in recycling are rising form the structure of the textiles, comprising of textile fiber blends, yarn and garment structures and well the components typical for clothing. In chemical separation methods, the sensitivity of both of the polymers defines strict limits to which conditions are possible without depolymerizing or damaging markedly either of the main components. In this paper we discuss the challenge of available processes.

Keywords: polyester-cotton textiles, fractionation, plastic, recycle textile materials

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Introduction

Waste problem on plastic relates to micro plastic issue and synthetic textile fibers pronounce part of the problem. Polyester is dominant among the textile materials, comprising of various copolymers of terephthalic acid. The non-biodegradable textile fiber fragments do create environmental risk through access to food chain.

Life cycle assessment is another aspect to collect and recycle textile materials. Until now, however, the recycling technologies for mixed textile materials are some limited lacking competitiveness against virgin materials.¹ Raw-material base of oil is not running short, but more affordable sourcing of raw materials are of great interest, if possible through recycling.² Motivation for the discussion is increasing demand of suitable products.

Main challenges in the polymer fraction separation

Material recycling of textiles have several challenges. This is why we should consider repair and reuse of preowned textiles as far as possible. Eventually, however all the textiles will wear out and become impractical for their original use.

Inherently the problems are rising form the structure of the textiles, comprising of textile fiber blends, yarn and garment structures and well the components typical for clothing. Recovery of the fiber constituents in their original polymers requires recognition, sorting and fractionation either mechanically or chemically.

Main textile fibers are polyester and cotton, which differentiate on chemical structure on high hydroxyl groups on cellulose. This means marked surface energy difference, which should enable separation. The structure of textile prevents this option in many occasion. Similarly, density difference is hard to apply, when the fibers are bind tight together. Flotation, cyclones or any traditional mechanical separation is not sufficient if textiles are not as single fibers or pulverized to dust.

In chemical separation methods, the sensitivity of both of the polymers defines strict limits to which conditions are possible without depolymerizing or damaging markedly either of the main components. Typical contemporary solution comprises to collect either cotton as sugars or polyester as hydrolysates. Problem remains that 3rd generation sugars fermentation to fuels nor terephthalic acid recovery to polymeric grade are economically unattractive.

Extraction is alternative to avoid polymer breaking to monomers. Effective polymer solvents are yet available for cellulose and polyester. There are several issues on this road as well. Viscosity of the polymer solutions tend to be high. Risk of gelation, gel formation or partial precipitation together with viscosity challenge polymer solution filtering processes.

Impurities are not allowed in polymer solution before applying or recrystallizing it. Typically, dilute solutions are simple to handle. High volumes of solvents means also high flux in solvent recovery and high costs.

How to separate cellulose and polyester fractions simultaneously as polymers

Mechanical textile opening is a dry process having reputation as low carbon and minimum water footprint. Energy consumption could be, however, of some importance. Losses to fines formed in carding could become of some importance.

Textile mechanical opening does not fractionate fiber materials. Only slight concentration difference are possible between produced refined fibers and fiber dust from weaker fibers. Actual fractionation methods are necessary if one material only containing fractions are the target.

Gravity difference of cotton and polyester is marked 0.16 g/cm³, while densities are 1.54 and 1.38 respectively. This is clearly sufficient for separation. The values of dielectric constant are 5.18 for ramie, 4.46 for jute, 4.23 for cotton and 4.22 for polyester at moderate temperature, which are minor differences. However, polyester is higher in triboelectric series and charges higher to several thousand volts while that for cotton is just few hundred volts. Polyester charging might reduce with surface treatments.

Surface energy of polyester is 46 dyne/cm and contact angle 90 degree. While polyester is hydrophobic untreated cotton is clearly hydrophilic, their surface properties are object of modification in textile applications by purpose for desired properties or just by coloring. As a conclusion, density provides most attractive separation method for separate individual fibers or fines.

Chemical fractionation divides in methods of partial or full depolymerization and dissolving polymers.³ Enzymatic method may be somewhere in between.⁴ Complete de-polymerization of either cotton

to sugars or polyester to its monomers are most common alternatives for chemical recovery. In other words, these methods destroy fully polymer structure and bring us back to purification of monomers, re-polymerization and benefitting side streams typically as low value components.

Partial de-polymerization leads decay of polymer molar mass, which makes the particle made of the polymer more fragile and simple to mill in fines. The mechanism is typical for degradation of all polymeric materials, and they form fines or micro-plastic under UV radiation, elevated heat, chemical like hydrolytic or enzymatically induced partial de-polymerization. The fines are the objects for mechanical separation.

When possible to form a water dispersion it enables use of hydro cyclone technology, which classify both according particle size but as well density. Alternative is to utilize different flocculation or foam separation technologies, where surface treatments of the fiber fragments may have defining effect on separation.

Dissolving, as another alternative, allows collection of oligomers or high molar mass polymers. Benefit is that purification simplifies and there is less need for re-polymerization. Dissolving stages logically arrange according to textile analytic series. To improve solubility, it is viable to reduce degree of polymerization for improve solubility, reduce polymer solution viscosity and avoid gelation.

Polymer solution is simple to drain out of the remaining phase. As a result, there is dissolved polymer phase and solid residual. Later may naturally contain impurities, need for later purification or separation. Solution phase suits for filtration. Solid phase needs typically rinsing with same solvent as applied in extraction. It is advisable to apply conditions, which do not lead to precipitation of the extracted polymer. The rinsing solvent suits to reuse.

There are multiple ways of cascading mechanical and chemical

stages, but that is the optimization for best available separation result in means of yield and selectivity.

How to reach economic process

Most essential features of economic concepts are those, which are simple, are operated at low temperature, and have minimum auxiliary and recycling processes. Most chemical recycling concepts require high purity of fraction, like over 95%. Further in the concepts, where polymers are depolymerized have more steps than concepts recovering polymers as polymers.

Dissolving methods do mean high solvent recycling streams. With 5% polymer content in polymer solution, this means 20 times higher solvent recycling than the main stream. As consequence energy consumed in pumping and purification may become marked cost. This is, however acceptable if polymer solution is to be applied in conversion process, like regenerated cellulose fibers.

In case partial de-polymerization, if separation is sufficient, benefit is that both polymers are possible to result as solid materials. This enables separate converting of the products after fractionation.

Further chemical recovery processes mean high temperatures and pressures like over 200oC and pressures up to 20 to 30 bar. Low temperature means not only low operation costs due served energy but lower investment costs also lighter machinery. Certain level of energy efficiency improvement is possible with energy balancing (utilization of lost heat), however with extra investment.

Comparison of process types

We made a level comparison of totally 16 reported process concepts. The processes reported in literature, dedicated or intended also for fiber-to-fiber recycling, are in Table 1. There are several other processes, which are for bottle-to-bottle or bottle-to-fiber. Later ones were not of our interest.

Table 1 Selected processes dedicated or intended also for fiber-to-fiber recycling. (EG = ethylene glycol, TA = tereftalic acid, NaTA = tereftalic acid sodium salt, BHET = bis (2-hydroxyethyl) terephthalate, and HMF = hydroxymethylfurfural from cellulose fraction.)

Process type	Main mechanism	Technology	Products
Mechanical	Mechanical	Open garding	Fibers
Partial degradation	Molarmass reduction	Mild hydrolysis	Fibers and polymer
Hydrolysis	Depolymerization	Subcritical water hydrolysis	
Hydrolysis	Depolymerization	Partial hydrolysis, solvent extraction	Polymers
Hydrolysis	Depolymerization	Alkaline hydrolyse, salt removal before polymerization	NaTA
Dissolving	Dissolving	Alkaline	Polymer
Dissolving	Dissolving	Ionic liquid	Polymer
Depolymerization	Fermentation	Enzyme	TA
Hydrolysis	Depolymerization	Hydrothermal, supercritical water	TA EG HMF
Dissolving	Dissolving	Ionic liquid	Polymer
Hydrolysis	Depolymerization	Alkaline hydrolysis by microwave, salt removal before polymerization	NaTA
Glycolysis	EG decomposition	Ionic liquid, catalyst, polymerization from TA	TA EG
Glycolysis	EG decomposition	Metal catalyst	BHET
Dissolving	Dissolving	Organic solvent	Polymer
Methanolysis	EG decomposition, MeOH ester interchange	180oC, no contaminants, NaCO3 catalyst, DMT repolymerization	DMT, EG
Glycolysis	EG decomposition	200oC, polymerization from oligomers	BHET oligomer

The process types were mechanical, partial degradation, hydrolysis, glycolysis, enzymatic de-polymerization and methanolysis. In the valorization was considered feedstock flexibility, technical readiness level, easiness of intermediate conversion, conversion rate for main

and side stream, already established plant size, chemicals and energy consumption, operation expenditure OPEX, capital expenditure CAPEX, lifecycle assessment LCA and safety of the process. Comparison is expressed in Figure 1.

Process type	Feedstock	TRL	Intermed	Conversion rate	Side stream conv.	Plant size	Chemicals	Energy	OPEX	CAPEX	LCA	Safety
Mechanical	Green	Green	Green	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Green	Green
Partial degradation	Green	Green	Green	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Green	Green
Hydrolysis	Green	Green	Green	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Green	Red
Hydrolysis	Green	Green	Yellow	Green	Green	Green	Orange	Yellow	Orange	Orange	Yellow	Red
Hydrolysis	Green	Orange	Green	Green	Green	Green	Green	Yellow	Orange	Orange	Green	Yellow
Dissolving	Green	Red	Green	Green	Green	Red	Green	Yellow	Orange	Orange	Green	Green
Dissolving	Green	Red	Green	Green	Green	Red	Green	Yellow	Orange	Orange	Green	Green
Depolymerization	Green	Green	Green	Red	Orange	Yellow	Green	Orange	Orange	Orange	Green	Green
Hydrolysis	Green	Red	Green	Green	Red	Red	Green	Yellow	Orange	Orange	Yellow	Red
Dissolving	Green	Orange	Green	Green	Green	Orange	Green	Yellow	Orange	Orange	Green	Orange
Hydrolysis	Green	Yellow	Yellow	Green	Yellow	Yellow	Green	Yellow	Orange	Orange	Green	Yellow
Glycolysis	Green	Green	Green	Orange	Orange	Green	Green	Yellow	Orange	Orange	Green	Yellow
Glycolysis	Green	Green	Green	Orange	Orange	Green	Green	Yellow	Orange	Orange	Green	Yellow
Dissolving	Orange	Yellow	Green	Green	Green	Red	Orange	Red	Red	Red	Orange	Orange
Methanolysis	Yellow	Green	Yellow	Orange	Red	Green	Yellow	Red	Red	Red	Orange	Orange
Glycolysis	Orange	Yellow	Green	Yellow	Red	Green	Green	Yellow	Orange	Orange	Green	Yellow

Figure 1 Comparison of different chemical recycling systems with alternative partial degradation and dissolving concepts in several process aspects; from very good to less desired in color code from dark green, green, yellow, orange red to dark green (worst).

Process specific findings can be noted following things. Mechanical recycling is most flexible and resource scarce, but fiber quality may compromise. Partial degradation has promising feature if high separation quality achieved. Hydrolysis seems a fair solution, but it may have some OPEX and CAPEX issues. Glycolysis is most common concept, having as well CAPEX and OPEX issues, and additionally concern on total yield including minor component conversion. Dissolving is promising but on conditions, that solvent recycling has solution. Enzymatic de-polymerization is yet in early development even if having promising sustainable features. Finally methanolysis is far too complex for competition with modern virgin petrochemical production.

For the future attempts main development needs are in the energy consumption, operation expenditure OPEX and capital expenditure CAPEX. It is evidently necessary to improve overall yield by means of recover both main components. This will lead to minimized losses, but require several process improvements in most of the concepts. Further would be beneficial improve ability to benefit of alternative recycle streams of polyester as well in same process.

Conclusion

As a conclusion the contemporary processes separation cotton from polyester rich textile waste, seem to have five concerns. Scale-up of various processes are still under development. Most of the processes are complex or contain operations that increase investment costs, operational costs or both. Applying solvents or high temperatures have as well negative effect on both OPEX and CAPEX. Robustness of the feedstock is markedly limited with most of the processes. Most of the available process concepts are unable to recover both main polymer components as value added product or intermediate.

We can see potential to solve the dilemma of mixed polyester and cotton waste textile recycling. Several improvements are essential, especially when success of the concept bases on cost competitive production instead of green value.

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Conflicts of interest

Authors declare that there is no conflict of interest.

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