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A Systematic Review of Recycled Cotton Fibre Blending Practices, Challenges and Recommendations

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ABSTRACT
The speed with which fashion trends change encourages excessive consumption and inadequate management of textile waste. Therefore, the use of recycled cotton fibres (RCF), as a sustainable alternative, by textile industries has taken on greater relevance; however, there are uncertainties about its implementation and appropriate method. Therefore, this review aims to identify the method of blending recycled cotton fibres to produce new yarns. For this, the PICO method was used to define the research questions and keywords; Then, it was complemented with the PRISMA methodology to search for information in the Scopus and ProQuest databases. The information found was analyzed in an Ishikawa diagram and later in a Pareto diagram. Finally, it was concluded that the most suitable RCF blending method is 50% VCF with 50% RCF. If more RCFs were added, the products would not meet the optimal quality measures for their production and marketing. Likewise, the main limitations to implementing the method are the adequate selection of the type of recycling, a high financial outlay for the classification of fibres legal loopholes such as the lack of supervision by the government, and inadequate implementation of the extended responsibility policy (EPR). Furthermore, the lack of specific regulations on textile recycling and the absence of certifications for companies that adopt sustainable practices represent additional obstacles.

KEYWORDS
textile industry, recycled cotton fibres, textile waste, recycled yarn, sustainability

INTRODUCTION

In recent years, with changing fashion trends, consumption has resulted in clothing being discarded well before its end of life. From 2022 to 2030, notable growth in textile production is anticipated, projected to reach around 149 million metric tons worldwide. The increase is 30.87%, which reflects a per capita increase of approximately 3.5 kilograms per person compared to the previous decade. This suggests a significant expansion in demand for fibers, especially synthetic fibers, which occupy 64% of the market, with polyester accounting for 54% [1]. Cotton fiber is in second position as the most used in the textile industry, generating 11.6 million tons of waste annually around the world [2]. Textile waste refers to the fragments, remains or products discarded during the process of manufacturing, use or disuse of textiles. This waste may include fabric offcuts left over from production, clothing or textile products that have reached the end of their useful life and are no longer usable in their original form [3]. They are categorized into three main groups according to their origin: pre-consumer waste, which comes from the manufacturing and processing of textiles before reaching the final consumer; post-consumer waste, which is generated after textile products are used and discarded by consumers; and post-industrial waste, which originates from the manufacturing processes of the textile industry [4]. This classification helps to understand the diversity of textile waste sources and allows the development of specific recycling methods to address each one.

At the same time, the proliferation of this textile waste has become a growing challenge, as greenhouse gas emissions from manufacturing EPRresent 10% of total global emissions [5]. On the other hand, other experts agree that approximately 80% of the total environmental impact derived from the use of clothing is directly related to its manufacturing process, this percentage is broken down into 16% in the production of fibres, 10% in yarn manufacturing, another 10% in fabric production, 23% in wet treatment, 16% in clothing and 1% in transportation [6,7]. In 2019, a study detailed that fifteen textile dyeing establishments in Bangladesh used 9,611.26 million liters of water and 17,689.43 megawatt-hours of energy to produce 7,602.88 tons of coloured fabrics [8]. Likewise, in the European Union for the total manufacturing of clothing, and footwear, among others, approximately 4 billion cubic meters of surface water were used [9]. Surface water or "blue water" refers to available surface water resources such as rivers and lakes, unlike "green water", which refers to rainwater stored in soils and used directly by plants [10]. The distribution of blue water used for clothing production reaches approximately 40%, while green water is mainly used in the production of clothing, accounting for around 30%. Within the latter, cotton manufacturing stands out as the most demanding, using around 20 billion cubic meters of green water [9].

Extensive research is being carried out to devise effective strategies for the reduction, reuse, and recycling of discarded textile materials [11]. One of these strategies is to use textile waste to recycle its fibres and transform them into yarn since around 75% of waste goes to landfills or is incinerated [12]. In Europe, landfills are saturated with textile waste, reaching an alarming figure of 4.3 million tons annually that are subjected to incineration. This translates into the shocking image of 60 garbage trucks full of clothes burning in the landfill every minute [13].

The information collected focuses on recycled cotton fibres (RCF), which come from recycled cotton textiles, while virgin cotton fibres (VCF) are extracted directly from cotton plants. The need to address this challenge sustainably becomes increasingly urgent, highlighting the importance of adopting practices that favour the conservation of resources and the reduction of the environmental impact associated with the inappropriate disposal of disused textiles. For this reason, policies have been created to support this initiative, which is extended producer responsibility (EPR). This implies that manufacturers and producers assume greater responsibility in all stages of the life cycle of their products, especially in terms of waste management.

In the case of China, being one of the main textile producers, regulations and policies have been implemented to control pollution and encourage recycling. The ban on importing foreign textile waste has promoted sustainable practices in countries such as France, which has adopted the Extended Producer Responsibility (EPR) policy [14]. Nonetheless, with the ban, we depend exclusively on national sources to obtain recyclable materials. This change can pose challenges in terms of the availability and quantity of recyclable materials, so regulations must adapt. For example, the company Aidishou collects waste via request from its mobile application and then recycles it [15]. Likewise, the number of companies that are responsible for recycling does not cover their extensive geography and not all of them have complete recycling for all fibres [16]. On the other hand, in Switzerland, unlike China, there is currently no known regulation that exerts legal pressure to prevent or promote the recycling of this waste. Nevertheless, there is self-interest, as reflected in a survey conducted with 13 companies in the country showed that they want to recycle their textile waste, but they need more resources for the entire process; Therefore, it is more profitable for them to pay to incinerate it than to invest in advanced recycling methods [17], since the garments they manufacture are composed of different fibres, 50% are synthetic fibre, 35% mixed fibre and 15% natural fibre [17], so diverse recycling methods are needed. However, the investment required to establish and maintain these types of large-scale facilities can be challenging. Exceptions have been made, such as Texaid, which is a large company responsible only for recycling post-consumer clothing [16].

In Peru, the responsibility for managing textile waste falls on the companies that generate it, who must present annual minimization plans to the Environmental Evaluation and Control Agency (OEFA). However, during the period from 2018 to 2021, only some companies complied with this obligation, and most of them only indicated the amount generated in tons, without providing details on how they managed this waste. This lack of transparency can lead to inconsistent interpretations, limiting producers' ability to fulfil their expanded responsibilities. The lack of awareness about textile waste management in Peru makes it difficult to implement efficient recycling systems, which contributes to unsustainable production habits and inadequate waste management, resulting in damage to the environment.

Although recycled cotton fibres (RCF) are a promising solution for the reuse of waste in Peruvian textile companies and thus contribute to the reduction of environmental pollution, they have not yet been put into practice since there is no adequate method to mix RCF to obtain good quality cotton threads, because several studies disagree on the appropriate percentage that this should have and the tests that should be considered when putting it into practice. It is also necessary to discover whether all waste is suitable for recycling and how post-consumer garments selected for recycling are sorted, such that proper selection would compromise the fibre quality of the yarn.

For this reason, the motivation behind this review is to identify the challenges that textile industries face when carrying out the recycling process and how these challenges can be addressed to improve the quality of the yarn and thus put it into practice in different companies in the Peruvian textile sector. Therefore, the general objective of this work is to identify the RCF blending method as an alternative to managing waste in the Peruvian textile industry. Therefore, the specific objectives are to evaluate the need to establish textile waste management policies, recognize the role of recycling and describe the characteristics of the classification of textile fibres for the recycling process.

METHODOLOGY

To begin with, the PICO method was used, of which the letter C was not used because it is considered more appropriate for medical issues unrelated to the subject matter, and for this reason, it was left blank. Then, the general question was posed with the words defined in each letter of the PICO, and the specific questions were drafted.

Then, keywords were assigned according to the description of each PICO letter, as shown in the following table.

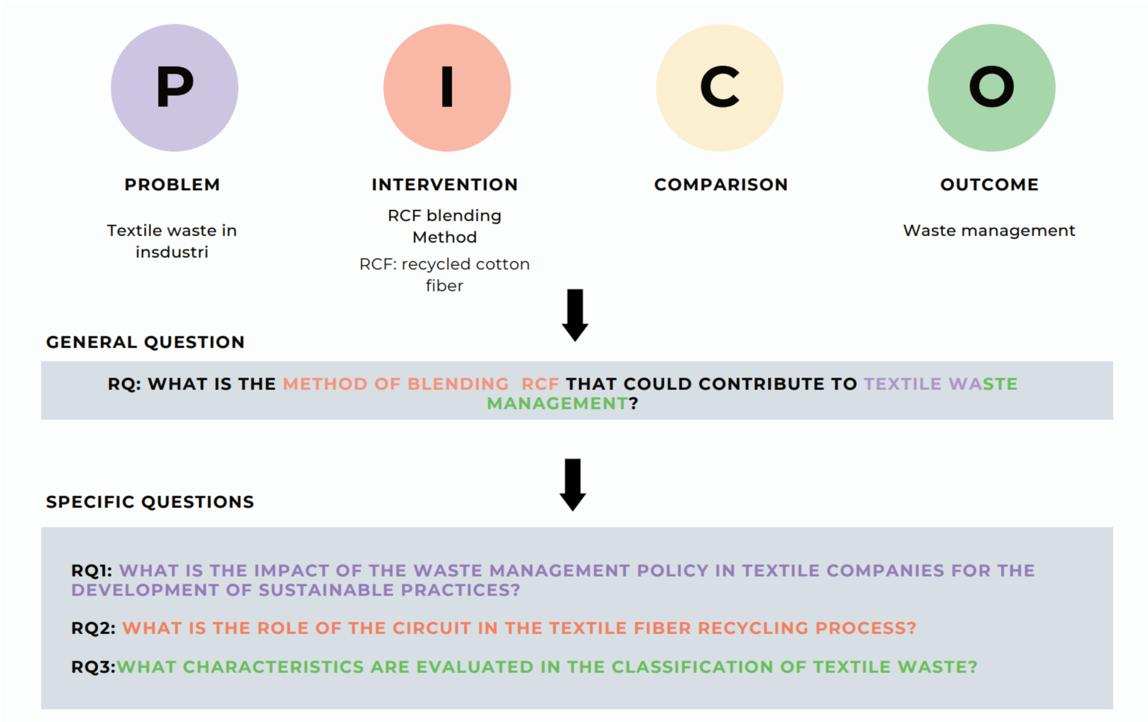

Figure 1. PICO diagram for a given investigation

Table 1. Keyword search equation for Scopus and ProQuest databases

	Word	Description	Search equation
P	Problem	Textile waste	"fabric industry" OR "the apparel industry" OR "The fashion industry" OR "the textile manufacturing sector" OR "Textile industry"
I	Intervention	RCF blending Method	"recycled cotton yarn" OR "recycled cotton fibres" OR "Cotton fibres" OR "reused cotton fibres" OR "recycled yarn" OR "Fabric Quality" OR "Textile waste" OR "clothing waste"
C	Comparison	___________	___________
O	Outcome	Waste management	sustainability OR "Ecological sustainability" OR "Green sustainability" OR "Sustainable development" OR "Environmental responsibility"

The Boolean operator OR and the symbols (" ") were used to elaborate the equation for searching and retrieving information in the Scopus and ProQuest databases.

Subsequently, the PRISMA methodology was used in a flow chart to filtrate the studies.

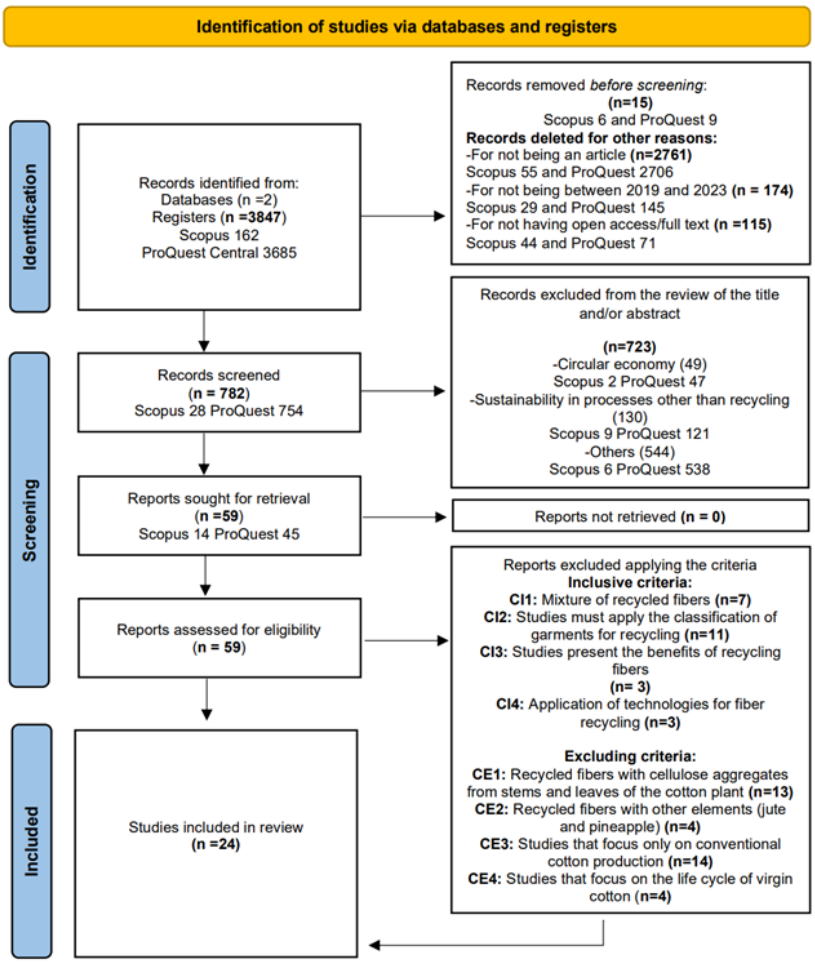

Figure 2. PRISMA diagram for study filtering [18]

When the search equation was performed in the databases, 162 results were obtained for Scopus and 3,685 in ProQuest, a total of 3,847 results. Continuing with the identification, the records eliminated before screening were 15 for duplicates, 2761 for not being articles, 174 for not being between 2019 and 2023, and 115 for not having open access or full text. After this first elimination, 782 articles remained; for the records screening, 723 were excluded by title and abstract, thus having 59 retrieved publications. Continuing with the review of the full texts, the inclusion and exclusion criteria were applied.

Inclusive Criteria (IC):

- IC1: Recycled fibre blend (n=7)
- IC2: EPRort must apply garment sorting for recycling (n=11)
- IC3: EPRort shows benefits of fibre recycling (n= 3)
- IC4: Application of technologies for fibre recycling (n=3)

Exclusionary Criteria (EC):

- EC1: Recycled fibres with cellulose aggregates from stems and leaves of the cotton plant (n=13)
- EC2: Recycled fibres with other elements (Jute and pineapple) (n=4)
- EC3: EPRort that focuses solely on conventional cotton production (n=14)
- EC4: EPRorts that focus on the life cycle of virgin cotton (n=4)

The criteria applied resulted in the exclusion of 35 articles. Finally, the studies included in the review resulted in 24 articles plus 17 complementary sources, 11 for the introduction and 6 for the RSL.

Main Objective (MO):
MO: Identify the RCF blending method that contributes to the management of textile waste.

Specific Objectives (SO):

- SO1: Evaluate the need to establish textile waste management policies.
- SO2: Recognize the role of the circuit in the textile fibre recycling process.
- SO3: Describe the characteristics of the classification of textile waste for the recycling process.

Of the 24 studies, a pattern was found in 6 themes EPReated with greater frequency, which became the categories analyzed. Therefore, a reference table was made detailing the mention of each category per study.

Title	Author(s)	Journal	Year	Categories				
				post-consumer textile	fiber classification	Recycling	Policy	RCF
A Delphi-Regnier Study Addressing the Challenges of Textile Recycling in Europe for the Fashion and Apparel Industry	Josephine Riemens Andree-Anne Lemieux Samir Lamouri and Léonore Garnier	Sustainability	2021	X	X			
A Review on Textile Recycling Practices and Challenges	Jeanger P Juanga-Labayen Idefonso V Labayen. and Qiuyan Yuan	Textiles: New Research Trends for Textiles	2022	X		X	X	
A Systematic Literature Review for the Recycling and Reuse of Wasted Clothing	Xiufen Xie Yan Hong. Xianyi Zeng Xisoqun Dai, and Melissa Wagner	Sustainability	2021	X	X	X	X	
Comparative Gate-to-Gate Life Cycle Assessment for the Akali and Acid Pre-Treatment Step in the Chemical Recycling of Waste Cotton	Lucas Rosson and Nolene Byrne	Sustainability Life Cycle Assess ment in Materials Engineering and Sustainability	2020	X		X		
Decision-making Algorithm for Waste Recovery Options. Review on Textile Waste Derived Products	Anda Zandberga Silvija Nora Kalnins and Julija Gusca	Environmental and Climate Technologies	2023	X	X	X		
Development of Natural Fiber-Reinforced Semi-Finished Products with Bio-Based Matrix for Eco-Friendly Composites	Claudia Mohl, Timo Weimer, Metin Caliskan, Stephan Baz Hars. Jürgen Bauder, and Gotz T. Gresser	Polymers	2022	X				
Eco-Sustainability of the Textile Production:Waste Recovery and Current Recycling in the Composites World	Antonella Patti, Gianluca Cicals and Domenico Acierno	Polymers	2020	X		X		
Effects of waste cotton usage on properties of OE-rotor yarns and knitted fabrics	Kilic Musa, Kaynak H Kübra, Kilic Gonca Balci, Demir Murat and Tiryaki Eflatun	Textile Industry	2019	X				X
Identifying the potential for circularity of industrial textile waste generated within Swiss companies	Melanie Schmutz and Claudia Som	Resources Conservation and Recycling	2022		X			
Investigation of the Physical Properties of Yarn Produced from Textile W aste by Optimizing Their Proportions	Hafeezullah Memon, Henock Solomon Ayele, Hanur Meku Yesuf and Li Sun	Sustainability	2022	X		X		X
Possibility Routes for Textile Recycling Technology	Damayanti, D., Wulandari, LA, Bagaskoro, A., Rianjanu, A., & W u, H.-S.	Polymers	2021	X	X			
Qualitative clas sification of woven fabrics produced from recycled threads of cotton and blends	Mihriban, K.	Textile Industry	2020	X				X
Quality assessment of fabrics obtained from waste	BEKIR, Y.	Textile Industry	2022	X				X
Recycling technologies for enabling sustainability transitions of the fashion industry: status quo and avenues for increasing post-consumer waste recycling	Eppinger E.	Sustainability: Science, Practice and Policy	2022	X	X	X		
Strategies of Recovery and Organic Recycling Used in Textile Waste Management	Wojnowska-Baryta I., Bernat, K., & Zaborowska, M.	International Journal of Environmental Res earch and PublicHealth	2022		X			
Textile and Product Development from End of-Use Cotton Apparel: A Study to Reclaim Value from Waste	Cao. H., Cobb, K, Yatvitskiy, M., Wolfe, M., and Shen, H.	Sustainability	2022	X				
The Quality of Blended Cotton and Denim Waste Fibers: The Effect of Blend Ratio and Waste Category	Kanan, M. W annas B. Barham, AS, Ben Has sen. M. & Assaf. R.	fibers	2022	X				
State of the Art in Textile Waste Management: A review	Thang K.H.D	Textiles	2023	X	x	x	x	
Recycling of Nanocellulose from Polyester-Cotton Textile Waste for Modification of Film Composites	Srichola, P.; Witthayolankowit, K.; Sukyai, P.: Sampoompuang C. Lobyam, K.; Kampakun, P.: Toomtong R.	Polymers	2023			x		x
Sustainable Textile Raw Materials: Review on Bioprocessi ing of Textile Was te via Electros pinning	Suen, D.W.-S. Chan, E.M.-H.: Lau, Y.Y.; Lee, R.H.-P.; Tsang. P.W.-K; Ouyang S.; Tsang C.W.	Sustainability	2023		x	x		
Development of an Algorithm for Textile Waste Arrangement	Indrie. L: Ilieva, J.: Zlatev, Z.; Tripa. S.: Sturza, A.	Sustainability	2023		x			
Optimization of Textile Waste Blends of Cotton and PET by Enzymatic Hydrolysis with Reusable Chemical Pretreatment	Boondaeng A: Keabpimai, J.: Srichola, P.; Vaithanomsat P.: Trakunjae, C.: Niyomvong N.	Polymers	2023					x
Opportunities and Limitations in Recycling Fossil Polymers from Textiles	Bianchi, S.: Bartoli, F.: Bruni, C. Fernandez-Avila, C. Rodriguez- Turienzo, L.; Mellado-Carretero, J.: Spinelli, D.: Coltelli, M.-B.	Macromol	2023		x		x	
Regenerated Cellulos e Fibers (RCFs) for Future Apparel Sustainability: Insights from the U.S. Consumers	Chi, T.; Frattali, A: Liu, H.; Chen, Y.	Sustainability	2023					x

Figure 3. Analysis of categories by study

Table 2. Categories that answer specific PICO questions

PICO general question	Specific questions	Categories	Quantity mentioned
What method of blending RCF could contribute to textile waste management?	RQ1: What is the impact of the waste management policy in textile companies on the development of sustainable practices?	Policy	4
	RQ2: What is the role of the circuit in the textile fibre recycling process?	RCF	7
		Recycling	10
		Post-consumer textile	16
		Circuit	6
	RQ3: What characteristics are evaluated in the classification of textile waste?	Fibre classification	11

Subsequently, for each specific question, the categories that best fit to answer those questions were designated to obtain more concise answers at the time of answering the general PICO question. Next, an Ishikawa diagram was made with the six established categories.

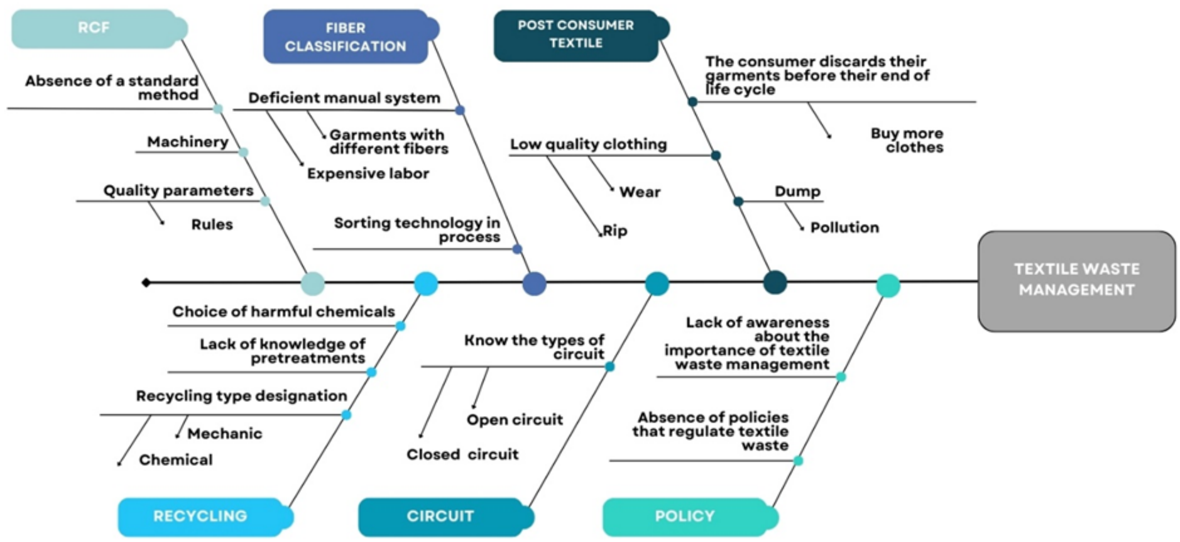

Figure 4. Ishikawa diagram on the management of textile waste

By category, the major causes that emerged from the large thorns and the minor causes from the small thorns were detailed. These were used to highlight the obstacles to the problem of textile waste management. The data were then plotted in a Pareto diagram.

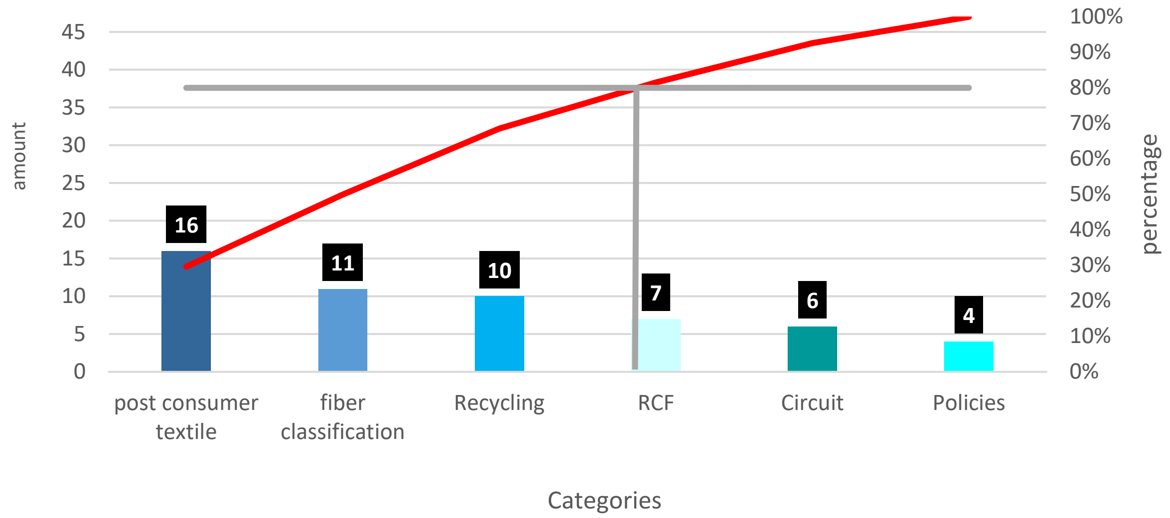

Figure 5. Pareto diagram on the management of textile waste

The categories with the highest number of mentions are post-consumer textile, fibre classification recycling and RCF EPRresenting 81% of the total number of studies reviewed. Since these are the most recurrent categories, they should be followed up more closely; this does not mean that the rest of the categories are unnecessary, only that the four main ones EPRresent a greater risk that impedes the management of textile waste.

Consequently, fashion is responsible for a significant environmental problem; due to this industry's increased production and demands, less than 1% of the materials used to manufacture garments were reused to create new clothes [19]. Post-consumer textile refers to clothing that has already been used by the consumer and then discarded; in the vast majority of cases, the clothing is in good condition.

On the other hand, a study investigated the flow of waste in Swiss garment companies and found that the main challenge is that there is no textile recycler to whom to send their waste, so most opt for incineration because it is affordable and costs approximately 154 Swiss francs per ton, equivalent to 172.33 dollars [17]. For this reason, not all companies have the capacity to invest in recycling since it is more profitable for them to pay for incineration, and if there were an established textile recycling site, they would be willing to take their waste, but with the condition that the price be similar or lower than incineration to be economically viable for them. Thus, there is an initiative in the manufacturing industry to change the route of their waste towards a more sustainable path; however, first, a reorientation and adjustments are required to develop a collective textile recycling plant [20].

Concerning Peru, the OEFA provided information on the annual waste minimization and management declarations of 39 large textile companies; for confidentiality reasons, their names will not be disclosed. Of the 39 companies, only 16 submit records of their textile wastes; of the remaining 23, no records were found; they only keep information on the amount of cones, inks, and chemicals, among other discarded items. The annual declaration follows Law No. 27314, which stipulates that this document must detail the volume of waste produced each month, the management plan applied, and the estimated production for the following year; nonetheless, not all of them comply with the requirements. Likewise, the use of textile wastes within the 16 companies was different. Only two companies recycled their waste in cleaning rags, 4 sold them, and 1 of these companies segregated them in the production line; unfortunately, the other organizations did not provide more details in their annual declaration or the management plan applied.

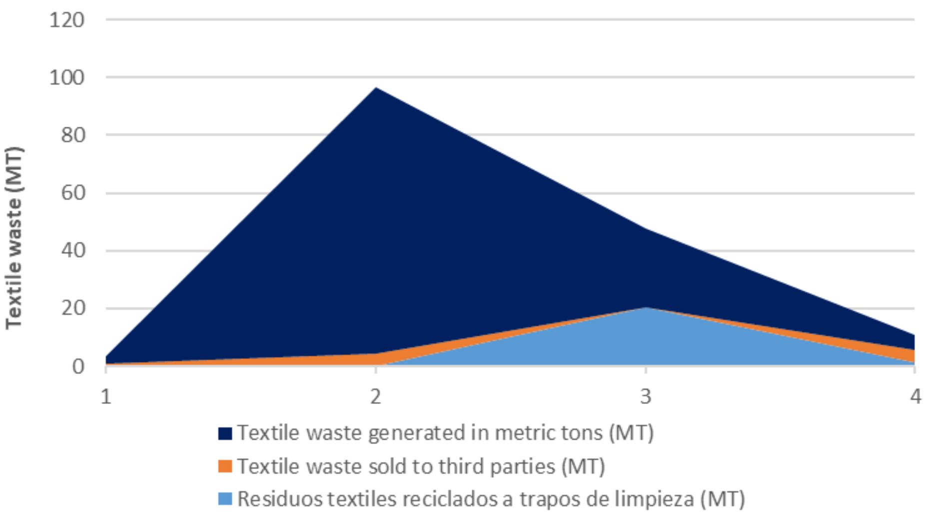

Figure 6. Annual Statement on Waste Minimization and Management

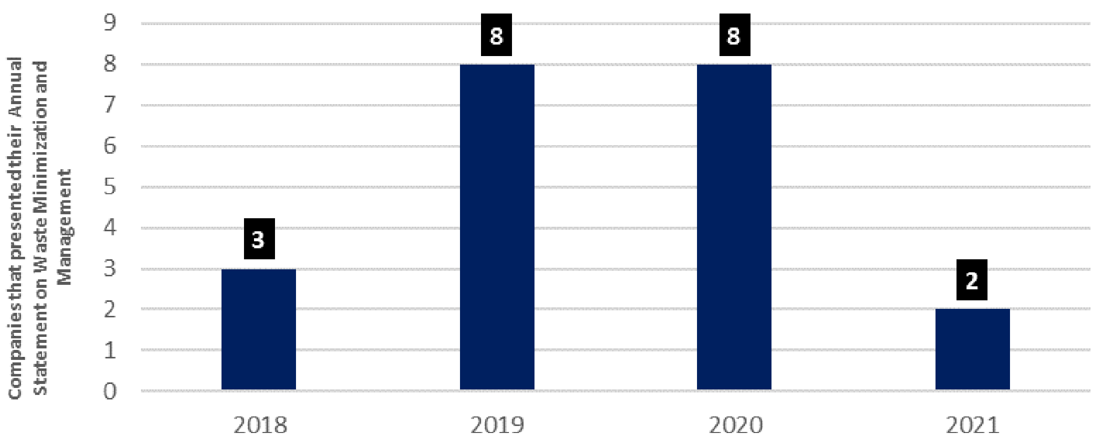

Figure 7. Numbers of textile companies that present their minimization plan

For good textile waste management, it is necessary to recognize and classify them according to the type of fibre; therefore, the fastest alternative is to hire labour to take care of this work. Likewise, it needs to be taken into account that manual classification is very expensive in large-scale processes [21]. Hence, an alternative is the creation of a hybrid algorithm for decision-making with multicriteria to evaluate the recovered textile products [22].

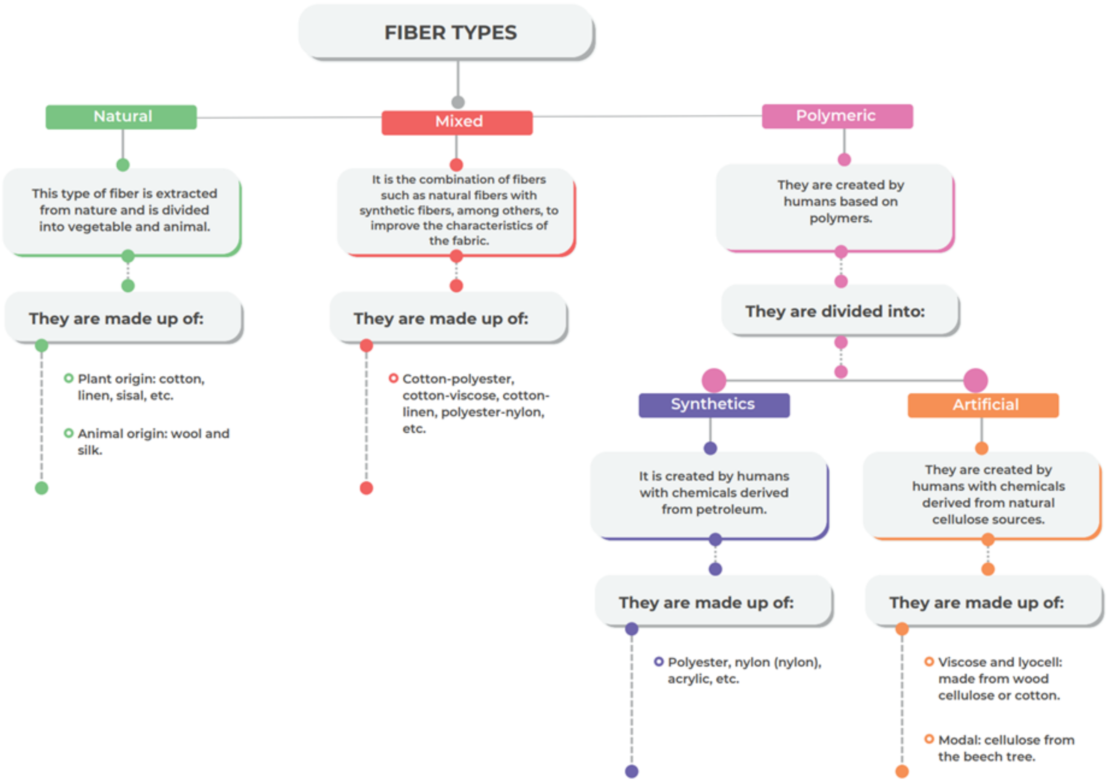

Figure 8. Fibre types

Separation by type of textile fibres simplifies the recycling process synthetic, artificial, and mixed fibres were created to improve the properties of natural fibres, creating new types of fabrics with varied characteristics. Polymeric fibres are composed of polymers, and these are formed from a group of monomers through chemical processes or petroleum resources, hence the division into synthetic fibres.

Mechanical recycling, which involves chopping and shredding into smaller fibres, is a physically force-based process with a production capacity of 5,000 to 36,000 tons per year [23]. This method is versatile, allowing the processing of various textile wastes, materials (natural, synthetic or blends), textile products (yarns, fabrics, used garments or carpets) and structures (knitted, woven or non-woven) [24]. However, it faces the challenge of reducing the length of the recycled fibre by up to 40%,

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complicating its use in closed circuits [25]. However, Purfi has presented an innovative solution for mechanical recycling, using a longer production line and a special treatment to maintain the original length of the fibre, this technology is already operational [26]. In this context, recycling is presented as an excellent option for the subsequent use of garments. But if you only want to separate the cotton fibres, an alternative is chemical recycling, which dissolves the waste in a chemical solution and decomposes it through depolymerization to obtain chemical products such as cellulose, liquids or gases, better preserving the quality of the cotton fibres [27].

Another point is to use a pretreatment with sulfuric acid at 0.5% by weight and deionized water at 1% by weight, depending on the concentration of the cotton; this helps the dye to be retained in the fibre and has been shown to remain in the fibre through regeneration and fabric production [28], then the recycling that best fits either mechanical or chemical is chosen, on the contrary, another study uses sulfuric acid pretreatment at a concentration of 99.8% along with sodium hydroxide and zinc chloride, according to ASTM-D5103-07 and then uses RCF for mechanical recycling [29]. For man-made or mixed fibres, it is recommended to apply a pretreatment and then use processes such as pyrolysis and enzymatic hydrolysis [30]. Complying with the quality standards for yarns, fabrics, and clothing can be produced [2].

In addition, the plan should specify the type of circuit the recycling plant will cover since a survey of Swiss textile companies established that it was necessary to know the type of circuit so that their wastes could be used to the maximum according to their fibre composition [31]. It has been investigated how effective recycled cotton fibre (RCF) is in recycling as much fibre as possible in such an optimal blend percentage between virgin cotton fibres (VCF). RCF is proposed for the transformation of these fibres to yarns; for this, the proportions of 75% VCF-25% RCF, 50 % VCF-50% RCF, and 25% VCF-75% RCF were used, which passed through an OE rotor spinning machine and were subsequently evaluated by seven quality criteria [32], another article evaluated the following proportions: 20% RCF -80% VCF, 25% RCF -75% VCF, 30% RCF -70% VCF, 35% RCF -65% VCF, 40% RCF -60% VCF, 45% RCF -55% VCF and 50% RCF -50% VCF, the results were analyzed with the Design-Expert software, which evaluated that the best sample was 40% RCF -60% VCF [29], because as the percentage of RCF increases, more defects appear in the yarn. On the contrary, for the production of recycled denim yarns, it was shown that with 60% fibres, denim fabric was produced without signs of degradation in yarn quality [33].

Other authors analyzed the proportion of fabric quality based on recycled fibre yarns; for this, the following prototypes were created in 100% FAR, 100% VCF, 35% polyester - 65% RCF, 35% polyester - 65% VCF, 50% VCF - 50% polyester and 50% RCF -50% polyester, the adequate proportion was 50% RCF -50% polyester, which presented 79 defects [34], the lower the defect present in the fabric, the higher it's quality according to the Graniteville 78 system, which evaluates the defects and quality of the fabric, which rated the proportion 50% RCF -50% polyester as acceptable. Other more recent studies used hydrolysis to be able to mix other types of fibres other than 35% polyester with 65% cotton with PET to improve the properties of the fibres [35] and 60% cotton with 40% PET [36].In addition, it is essential to mix recycled fibres with virgin fibres in a particular proportion so that the properties of the yarn are better and the fabric presents fewer defects; from the sample of 54 fabrics produced, ten were evaluated, and the author suggests the mixture of 50% VCF and 50% RCF as the adequate [37], for this it is required to separate the textures and fibre type of the materials, to achieve a similar quality as if new raw materials were used. Moreover, the yarn behaviour in elongation and strength criteria are adequate [38]. However, more studies are still required on the standard criteria for yarn quality from recycled fibres.

RESULTS AND DISCUSSION

This review study, reveals a significant gap in organizations' management of pre-consumer textile waste. Despite growing awareness of the importance of minimizing environmental impact, the results demonstrate an alarming lack of effective monitoring in this regard, particularly in the Peruvian context.

Focusing on a EPRresentative group of 16 leading companies in the period from 2018 to 2021, it is confirmed that only this small group presented annual minimization plans. The total volume of textile waste reaches a significant figure of 126.99 tons; nevertheless, the magnitude of this amount is overshadowed by insufficient management practices.

Of this monumental amount, only 16.85% experience a second life through recycling, becoming cleaning rags. Surprisingly, only 7.95% is intended for sale, which raises questions about the subsequent traceability of these products in the market. It is even more disturbing that, after the commercial transaction, the destination of the remaining 85.17 tons of textile waste remains shrouded in mysterious silence.

This panorama highlights a prevailing urgency for substantial improvements in the management of pre-consumer textile waste. The lack of transparency and apparent disconnect in the traceability of this waste not only hampers efforts to minimize environmental impact but also underscores the pressing need for more rigorous oversight and stronger accountability in the Peruvian textile sector. This call to action seeks to drive significant changes that ensure more effective and sustainable management of textile waste for an environmentally responsible future.

It should be noted that if you want to create another textile recycling alternative other than the production of cleaning rags, you should transform textile waste into recycled fibre yarns; this is a good option for environmental conservation, although it requires a high investment in equipment and should be separated according to the type of fibre to preserve the maximum of its characteristics in recycling.

On the other hand, post-consumer textile waste has been shown to have a higher frequency of mention, given that it is evident that it is not controlled since it ends up in landfills, where it is exposed to a contaminated environment, full of garbage and other waste that only contaminates the soil and damages the environment. As a first result, it was identified that there is a relationship with the six categories worked on.

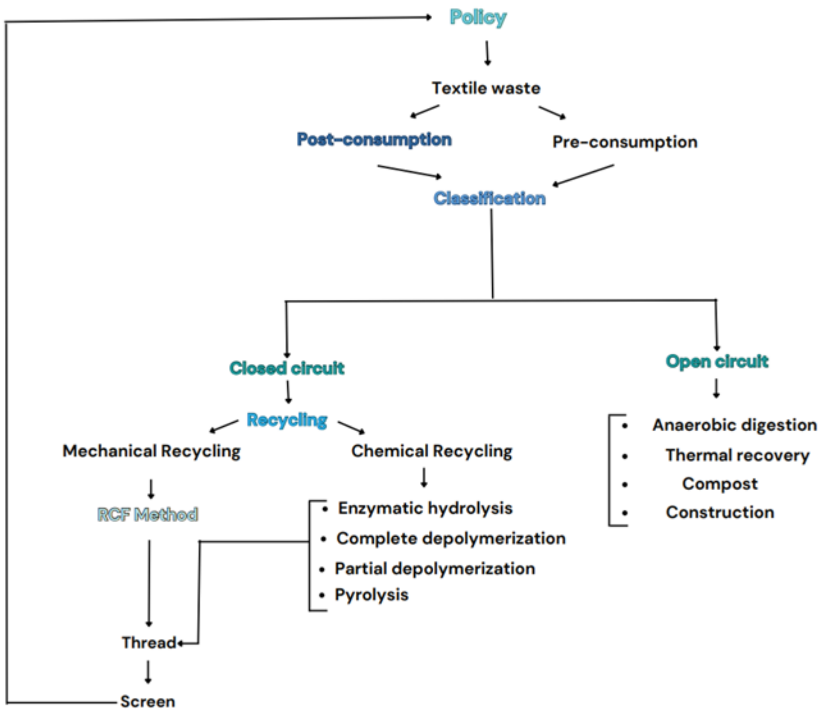

Figure 9. Relationship between the 6 categories analyzed

As can be seen in the figure, everything starts with the policy; Extended Producer Responsibility (EPR) focuses primarily on preventing environmental harm at the source, which in this context involves the design of the product or the product itself. In this way, it redefines the scope of the prevention principle by extending the causes and sources of environmental damage to the design stage [4]. In this sense, the EPR is interpreted as the extension of the responsibilities of producers to the design phase. post-consumption of its products, promoting environmental improvements for the entire life cycle of the products, with special emphasis on their recovery, recycling and final disposal [39]. The inclusion of the EPR in the regulatory framework is presented as an effective resource for improving the sustainability of the development of society, as it seeks to achieve the double objective of improving both product design and production systems, as an example, the extended producer responsibility (EPR) policy, France was one of the first in Europe to apply it to clothing at the end of its life cycle[27], and then the rest of the continent's countries have been encouraged to implement it in the collection of post-consumer textile products, achieving an increase of 13% annually[14], in that sense, with a well-defined policy on how it will be executed, who are the responsible authorities and how it will be supervised to ensure compliance with what is stipulated, it triggers good management of textile waste. However, for developing countries like Peru, the EPR policy focused on the textile sector would present gaps in implementation and compliance. Lack of resources to enforce regulations or industry resistance can be obstacles. They may not include all key players in the supply chain, such as importers or retailers, leaving gaps in shared responsibility. Added to that, more than half of the textile industry is made up of informality, limiting the fiscal control of the authorities. Since those in charge are established for both post-consumer and pre-consumer waste, they are classified, and their status is determined to direct it to the most appropriate circuit. In the case that is required to the closed circuit according to its type of fibre, it can go to chemical or mechanical recycling, and within the automatic is the RCF method; in this method, the waste becomes yarns, then becomes fabric to be used in the manufacture of new garments and again EPReats the cycle.

Next, the steps to be followed in the classification process were defined before going on to the mechanical recycling process by the RCF method and being converted to recycled fibre yarns, as shown in the following figure.

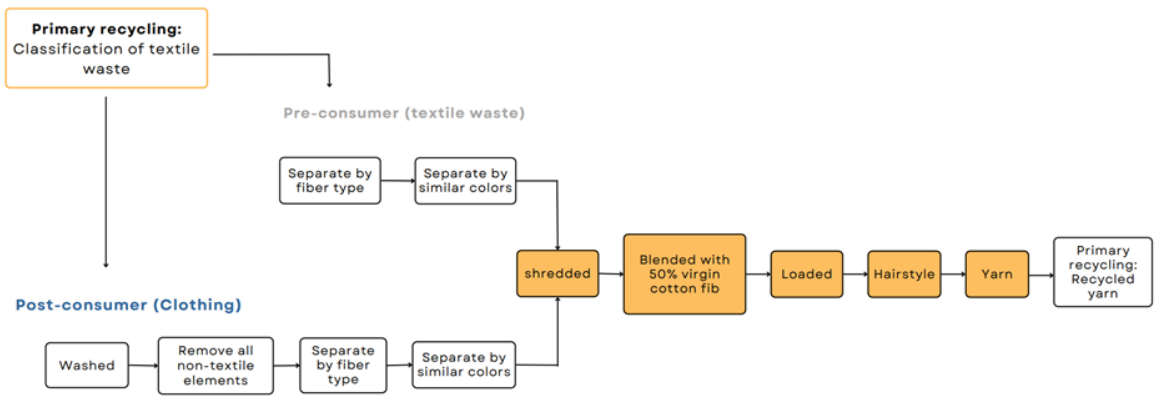

Figure 10. Processes to consider in the classification of textile and garment waste for the recycling of fibres into yarns

The quality of recycling largely depends on the textiles used as raw materials [24]. To guarantee this quality, it is essential to identify whether textile waste is pre-consumer or post-consumer. In the pre-consumer case, classification is carried out by type of fibre and similar colour tones. This colour classification makes it easier to make recycled fibre yarn without using dyes or water, resulting in a unique tone. After sorting, it is shredded and blended with 50% virgin cotton to maintain quality, followed by a carding process to smooth and remove static. Afterwards, it is combed to eliminate small knots and subjected to the spinning process, culminating in obtaining the final product.

In the post-consumer case, two additional processes are added before classification by fibre type. These processes involve washing and removing all non-textile elements, such as zippers, buttons, labels and patches. Manual categorization requires painstaking effort and can present challenges in recognizing specific fabric types [12], so algorithms are being developed to recognize patterns [40]. Automation of classification is crucial to achieving a textile value chain. circular. The most advanced technology in materials recognition today is near-infrared (NIR) spectrometry, which is already operational in Europe [41].

In this scheme, it is visualized that textile waste can be recycled four times; in the first place, it can be suitable to be recycled twice in the closed circuit, in other words, to be used in the textile industry to continue making garments, with the only difference that for the second recycling the 50% of virgin cotton fibres is no longer applied but this percentage would increase. For tertiary recycling, if the fibre is natural, anaerobic digestion is recommended because it decomposes natural elements. If this is not the case, controlled incineration is used for quaternary recycling. At the end of incineration, the ashes remain and can be used for composting.

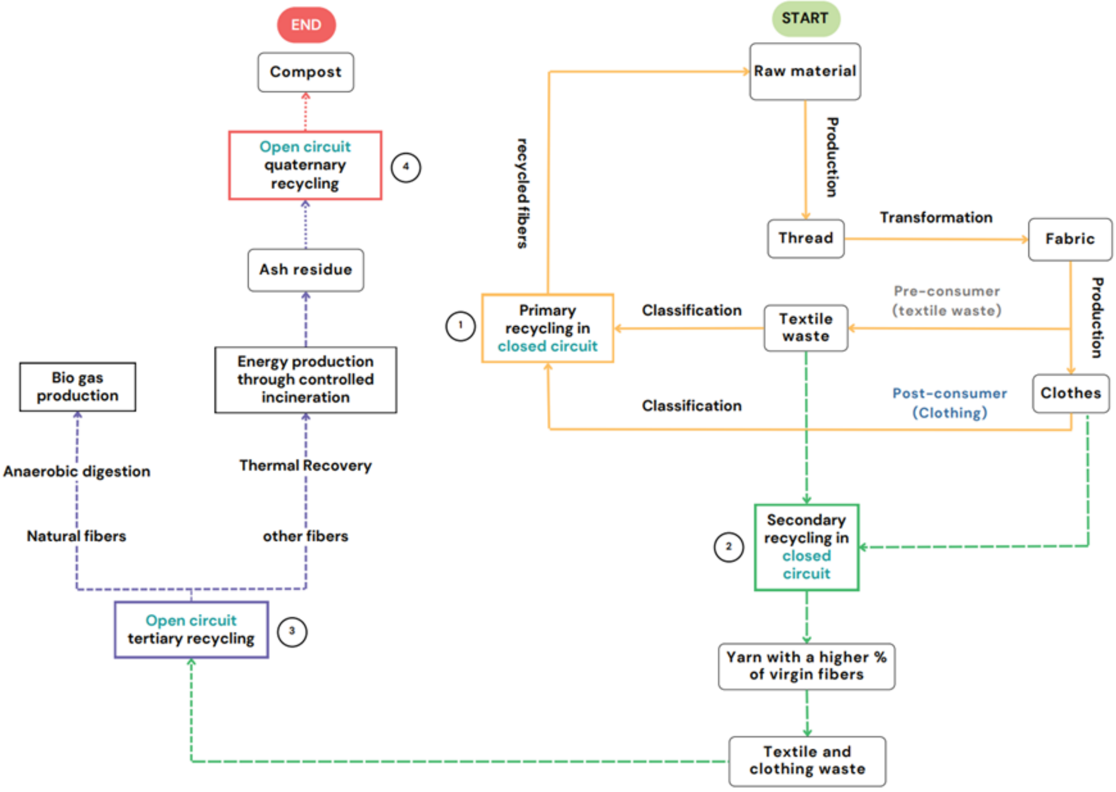

Figure 11. The importance of circuits in the textile recycling process

Following the research of Ref. [30], it is proposed that recycling can be used in four stages: primary, secondary, tertiary, and quaternary. However, the discussion varies in the tertiary recycling approach, where chemical recycling through pyrolysis and hydrolysis processes is considered and culminates with incineration in quaternary recycling. In the scheme in Figure 8, chemical recycling is not included since its process requires more research, and the work is focused mainly on mechanical recycling. What is new that has been introduced is the relationship between closed and open loops with the four recycling opportunities.

On the other hand, another study investigated the problems faced by India, another developing country, concerning textile recycling. To achieve this, various multi-criteria decision-making (DSDM) methods such as AHP and TOPSIS were used, which helped identify 30 obstacles [31]. These were identified through a literature review, supported by the opinions of a panel of 10 experts with an accumulated experience of 10 years in the field. Subsequently, the initial matrix of direct relationships is created, which is normalized, the complete relationship matrix is generated and the calculation of the influential and influenced impact values is carried out on a scoring scale from 0 to 4, finally, these obstacles were classified into 17 causes and 13 effects using a cause-effect diagram. A fuzzy DEMATEL method was then applied to select the most important obstacles and understand how they are related [31]. As a result, we identified five main obstacles to textile recycling in India, two of which are consistent with our review. First, the need for successful recycling models is due to the technical knowledge in textile sorting and the high investment cost of recycling processing. Secondly, it is necessary to review textile waste recycling control policies to keep the prices of recycled products affordable. To control the prices of recycled products, the government must establish specific policies and plans.

CONCLUSION

In this review, notable progress has been made in the commercial categorization of textile waste. Although expanding the practice of reusing and recycling can reduce the proportion that goes to clandestine landfills, it is essential to find a long-term sustainable solution to reduce waste in manufacturing and consumption associated with fast fashion.

As a general objective, the method of blending recycled cotton fibres (RCF) has yielded fundamental conclusions for the maintenance of the environment in the textile industry. The mixture of 50% RCF - 50% VCF is the most appropriate since it allows quality yarns to be obtained and favours the reduction of the volume of waste that is not managed, in addition to the conservation of resources and energy savings in production, thus contributing to the reduction of the carbon footprint. Positioning itself as a significant step towards waste reduction and resource conservation. In response to the specific objectives, the following was determined:

SO1: Evaluate the need to establish textile waste management policies.

The urgent need to establish specific textile waste management policies has been confirmed since textile industries have uncertainties about whether it is viable to practice a recycling culture. As evidenced in Peru, the adoption of a recycling policy alone does not guarantee effective compliance, before its legal loopholes must be corrected, since the policy in European countries is not managed the same as the policy in Latin America. , where the recycling culture is in process, therefore, an inspection must be added to monitor and control its execution, implement a traceability system, and establish a relationship between government entities, where they can establish specific regulations on textile recycling, provide certifications and financial incentives for companies that have the initiative to contribute to sustainability.

SO2: Recognize the role of the circuit in the textile fibre recycling process.

Understanding the critical role that the circuit plays in the textile fibre recycling process is essential, it is concluded that a well-established circuit facilitates the efficient collection of recycled fibres. This recognition highlights the need for a holistic approach that covers all stages of the circuit, from production to final disposal, to achieve effective and sustainable management of textile waste.

SO3: Describe the characteristics of the classification of textile waste for the recycling process.

Classification is the first step in the management of textile waste, since products based on FCR or any other type of recycled fibre would have a lower quality if they are not properly classified, since if the waste is very worn it cannot be used for recycling yarn. This review has focused solely on cotton and cotton-polyester fibres; However, future research needs to cover mechanical recycling with other types of fibres. Likewise, it is important to specify that all fibres are always suitable for mechanical recycling. and when there is no major wear, but for this some require prior pretreatment. Furthermore, most of the studies reviewed agree that it can only be recycled between similar fibres, otherwise it would affect the properties of the yarn.

The limitations in the RCF method are the state of the fibres; the greater the damage or wear, the fibres can no longer be recycled for recycling into yarn. On the other hand, future research should investigate recycling for the rest of the fibres in greater depth. because only scant information has been found on natural fibres (cotton) and synthetic fibres (polyester and PET). Likewise, it would be considered to regulate the modification of the fibres and establish a standard to know the % of fibres of each fabric with greater precision.

The implementation of textile recycling in companies faces certain limitations derived from existing policies, which still present significant obstacles. This problem has been underexplored in the literature, evidencing the need for a deeper and more detailed analysis in this regard. On the other hand, a sustainable approach suggests donating clothing before throwing it away, encouraging its reuse and suggesting recycling only when the life cycle of the garment has come to an end.

It is crucial to highlight that the economic viability of textile recycling, especially in collective recycling centres, depends directly on the cost of the service per kilogram recycled compared to alternatives such as incineration. In this sense, the research highlights the need for the price of the service to be competitive to ensure the profitability of these centres. This consideration highlights the importance of policies and cost structures that support the widespread adoption of textile recycling.

In terms of future perspectives, exploration of automatic sorting technologies is highly recommended, especially for large-scale recycling initiatives. These technologies, by processing considerable volumes with greater precision and time efficiency, could overcome challenges associated with manual sorting and boost the widespread implementation of textile recycling.

Additionally, there is a need to address specific aspects of chemical recycling in future research. The importance of providing quantitative data on the amount of water used in washing processes aimed at removing chemical solutions from textile fibres is highlighted. This approach will allow for a more complete assessment of the environmental impacts associated with chemical recycling, thereby contributing to scientific knowledge and informed decision-making in this area.

Finally, the present review has been restricted to consulting open-access articles, a decision that, although justified, suggests that obtaining a more extensive and detailed range of information would have significantly enriched our analysis. The limitation to open access sources has marked an initial framework, but the possibility of greater breadth and comparison of data is recognized if more diverse information were available. Despite this restriction, our work seeks to contribute significantly to the existing body of knowledge and serve as a starting point for subsequent research that can address the limitations noted. Transparency in methodology and reflection on limitations are essential components of scientific rigour, and this study strives to meet these standards, thus opening new opportunities for the expansion and continuous improvement of research in this specific area.

Author Contributions

Conceptualization – Stephany A and Franz M; methodology – Stephany A, Franz M and Monica O; formal analysis – Stephany A and Franz M; investigation – Stephany A and Franz M; resources – Stephany A and Franz M; writing-original draft preparation – Stephany A and Franz M; writing-review and editing – Stephany A and Franz M; visualization – Stephany A and Franz M; supervision – Stephany A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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