

Sustainable and Recyclable Materials for Seat Belt Webbing: Current Trends and Challenges

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Abstract

Seat-belt webbing is an essential part of the automotive restraint system and has a decisive role in occupant protection during collision events. Traditionally, seat belt webbings are made from synthetic fibers such as polyester and polyamide of petroleum origin because of their high tensile strength, controlled elongation behaviour and resistance to abrasion and durability in severe mechanical and environmental conditions. However, rising environmental concerns, fossil resources depletion and global sustainability commitment have strengthened the research in recycled and renewable alternatives for automotive safety textiles. The introduction of sustainable materials in seat belt webbing is especially difficult because these materials are subject to strict international safety requirements and have to provide uniform long-term mechanical performance. This review gives a thorough analysis of sustainable and recycled materials for seat belt webbing such as recycled polyester, recycled polyamides, bio-based polymers and hybrid material systems. Material processing routes, degradation mechanisms, fatigue and creep behaviour, regulatory requirements, manufacturing challenges and life cycle environmental impacts are critically examined. The review also identifies key areas for research and future direction that focus on facilitating the large-scale adoption of sustainable seat belt webbing without compromising occupant safety.

1. Introduction

Road traffic accidents are one of the major causes of deaths and serious injuries worldwide and are a major public health and socio-economic challenge. Passive vehicle safety systems like airbags, crumple zones and seat belts are meant to limit injury severity in collision events. Among these systems, the seat belt is widely acknowledged to be the most effective and universal restraint mechanism that can reduce the risk of fatal injury by as much as 50% for vehicle occupants[1].

The performance of a seat belt system is highly dependent on the mechanical and durability properties of the webbing material. In an impact, the webbing undergoes high strain rates and tensile loads and undergoes controlled elongation to absorb the kinetic energy of the impact and limit peak forces transmitted to the occupant. At the same time, the webbing must have enough residual strength to avoid rupture. These challenging requirements are regulated through international safety standards, like FMVSS No. 209 and UNECE Regulation No. 16, which define the minimum breaking strength, elongations, abrasion resistance and the resistance to environmental ageing[2].

Conventional seat belt webbings are mainly produced from high tenacity polyester and polyamide fibers produced from fossil resources because of their proven reliability and consistency. However, the manufacturing of virgin synthetic polymers is energy intensive and is a major driver of greenhouse gas emissions and environmental degradation[3]. In face of global sustainability targets and circular economy efforts, the automotive industry is turning to recycled and renewable material alternatives. The use of such material in safety-critical applications involves substantial technical, regulatory, and durability challenges and requires extensive evaluation and validation. In Figure 1, the seatbelt innovation roadmap is presented as a timeline from early development to emerging technologies.

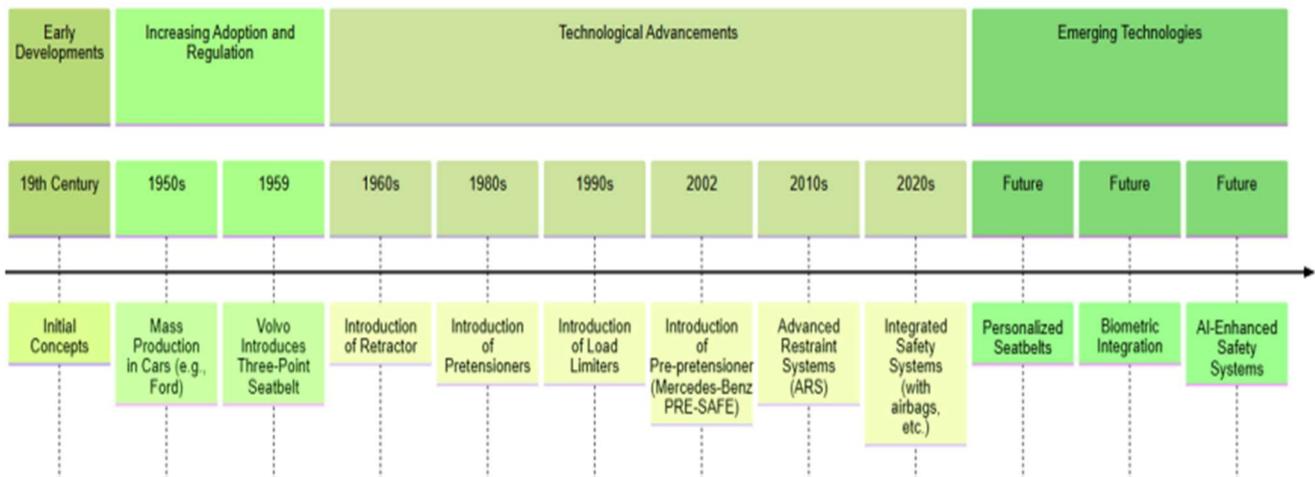


Figure 1. Seatbelt innovation roadmap.

1.1 Functional and Mechanical Requirements of Seat-Belt Webbing

Seat belt webbing needs to meet a particular blend of mechanical, physical and environmental criteria that are not common to the typical automotive textile. The tensile strength is the most important requirement since the webbing should have the capability to sustain extremely high loads as the crash occurs without tearing[4]. In extreme crash situations, tensile forces on the webbing may go as high as several kilonewtons and the material has to be able to sustain the structural integrity coupled with the effectiveness of restraint of occupants[5].

Besides strength, there is also the need to have controlled elongation which is needed to absorb energy. When the vehicle is in a crash, the webbing has to deform in a foreseeable and manageable fashion so as to discharge the kinetic energy and lower the peak forces conveyed to the body of the occupant[6]. Over-elongation may cause occupant excursion and consequently secondary effects on the interior vehicle parts, and under-elongation may cause great deceleration and serious injuries. Thus, a good balance between strength and extension is a basic design problem of the seat-belt webbing materials.

Another important performance criterion is that of abrasion resistance. The friction of seat-belt webbing with buckles, retractors, and anchorage points are performed repetitively during normal use. This mechanical action taken repeatedly during the service life of the vehicle can lead to wear on the surface of the vehicle as well as tearing and gradual weakening of the fibres of the vehicle. The webbing materials should therefore be very resistant to abrasion in order to be reliable in the long run[7].

It is also important that the environment is durable. The webbings used in the seat belts are subject to the ultraviolet radiation, high temperature, humidity and microorganisms during their service life. These may cause polymer degradation by photo-oxidation, thermal ageing as well as hydrolytic reactions which eventually lowers the mechanical performance. Durability, especially in the long term, is of high significance since the seat belts are expected to last up to ten to fifteen years of service. The ability of any recycled or sustainable material or material to be used in the webbing of the seat-belt should be able to prove the same, that is, it must exhibit the same mechanical stability and environmental ageing as an ordinary material[8].

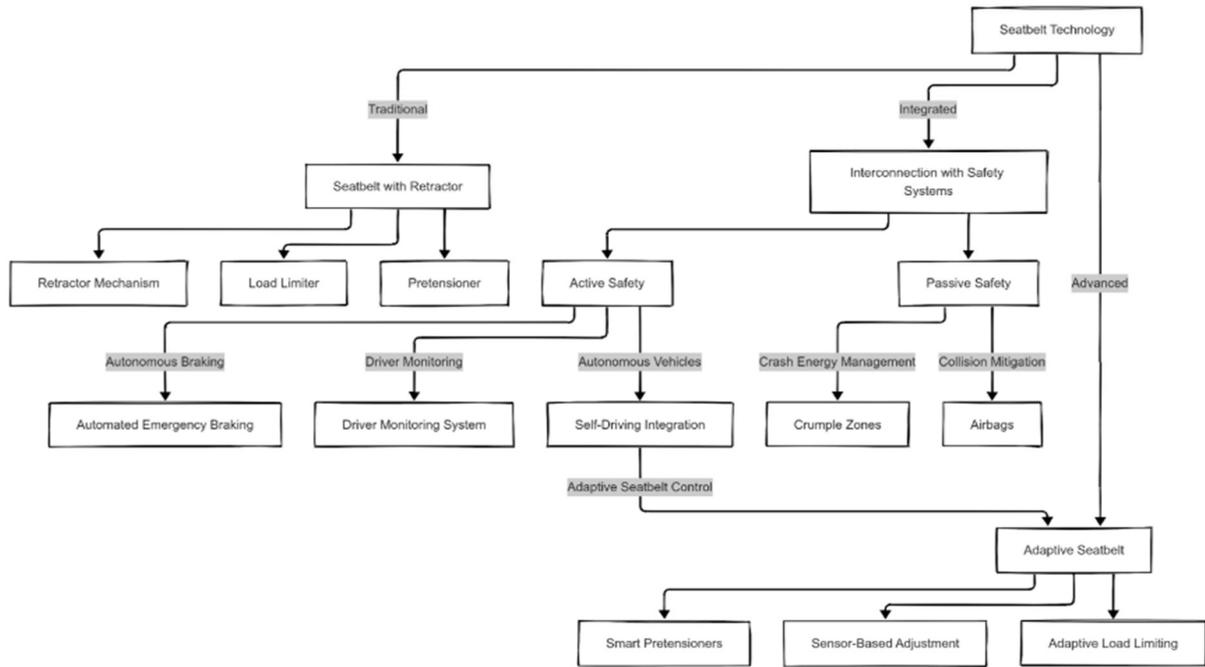


Figure 2. Conceptual overview of seatbelt technology.

In Figure 2, the conceptual overview of seatbelt technology is presented, in terms of traditional seatbelt, integrated seatbelt, and advanced seatbelt system.

1.2 Conventional Materials Used in Seat-Belt Webbing

Seat-belt webbing is predominantly made of polyester, primarily polyethylene terephthalate (PET), because it provides a good compromise between mechanical properties, long-term performance, and cost. Melt spun and then drawn to high levels of draw ratio, heat-set yarns formed from PET have a high degree of molecular orientation and crystallinity. Such microstructural architecture and good **dimensional** stability makes the polyester to be an ideal material for safety-critical applications with high tensile strength, low creep behaviour and excellent dimensional stability[9].

One of the advantages of polyester fibers is their low water uptake (below 0.5 % for many) irrespective to the type of service conditions, hence stable mechanical properties. This feature is particularly useful in automotive environments where humidity and temperature varies greatly. Accordingly, seat-belt webbings formed of a polyester yarn have uniform elongation property and long wear characteristics[10].

Polyamide fibers such as nylon 6 and nylon 6,6 have used in some cases for seat-belt applications because of their good toughness and abrasion resistance. The polyamides have a higher deformation energy absorption capacity, which can be advantageous based on the retention system design used[11]. But polyamides are naturally hygroscopic and tend to absorb large quantities of moisture from surroundings. Moisture uptake can change the mechanical properties, with elongation behaviour in particular varying due to performance within humid conditions (Morton and Hearle 2008). Such a limitation has hindered the broad application of polyamides as are used in conventional seat-belt webbings for automobiles ..

High-strength fibers, such as aramids and ultra-high-molecular-weight polyethylene (UHMWPE), contribute high strength-to-weight and impact resistance. However, the cost and elaborate processing of these materials restrict their use to advanced restraint systems rather than the mainstream car. While conventional materials offer superior performance, they are mostly derived from the fossil counterpart leading to renewed interest in sustainable approach toward this material[12].

2. Sustainability Drivers and Circular Economy Perspective

The automobile business is changing in huge ways mainly due to three reasons: firstly, a big push for a cleaner environment, secondly, governments have started imposing tougher laws, and thirdly, people have changed their expectations about the way companies should behave[13]. To tackle climate change and preserve natural

resources, authorities have set more ambitious goals for vehicle emissions and usage of recycled materials in car manufacturing. Automakers, on their part, have set high targets of not only incorporating recycled materials more than ever but also significantly cutting down on their greenhouse gas emissions and eventually going for a zero carbon supply chain[14].

The circular economy idea revolves around reusing materials, recycling them, and producing very little waste to prevent running out of resources and hurting the environment. One of the ways to make seat, belt webbing applications more circular is recycling polymers that come from either post, consumer or post, industrial wastes. Several life cycle studies have revealed that if a virgin polyester is substituted with a recycled one, then there is a great potential of saving up to 50 percent of the energy used. Moreover, the amount of greenhouse gas emitted can also be reduced by the same level, however, these depend on how efficient the processing is and the energy sources[15].

Nevertheless, there are quite a number of obstacles to overcome before fully applying the circular economy principles in safety components such as seat, belt webbing. For instance, recycled materials are usually confronted with problems such as change in the molecular weight and mechanical properties and since these properties are very important safety testing, it is a huge challenge to control them. Therefore, sustainable seat, belt webbing materials are not only expected to be engineered to perfection but they also need to be certified by a very reputable authority after going through rigorous testing[16].

3. Recycled Polyester (rPET): Processing Routes and Performance

One of the most attractive sustainable alternatives for automotive textiles is recycled polyester which is derived from post, consumer PET bottles. The reason for this is that PET waste is a widely available material, and the recycling infrastructure is well, established. The route that is most commonly used for mechanical recycling involves the collection of PET wastes, sorting, washing, shredding, and then doing melt reprocessing of PET waste to obtain the fibers[17]. The energy consumption involved in the manufacturing of recycled polyester is significantly lower than that of virgin PET production, and the recycled polyester manufacturing also results in lower greenhouse gas emissions.

However, the mechanical recycling process does bring along some material issues. Through repeated thermal treatments polyamide chains can be broken down into smaller ones, which results in a decrease in molecular weight and thus also of the intrinsic viscosity. This would deteriorate the tensile strength, elongation behavior, and fatigue resistance, which are very important seat, belt webbing performance characteristics (Al, Salem et al. , 2017). Figure 3 shows the scheme of the conventional recycling process of PET. The first step of recycling PET is the post-consumer PET bottles resized, and it became flakes. The common additive as a cleaning agent of PET used are caustic soda with the percentage of usage about 2–3% and detergents [18]

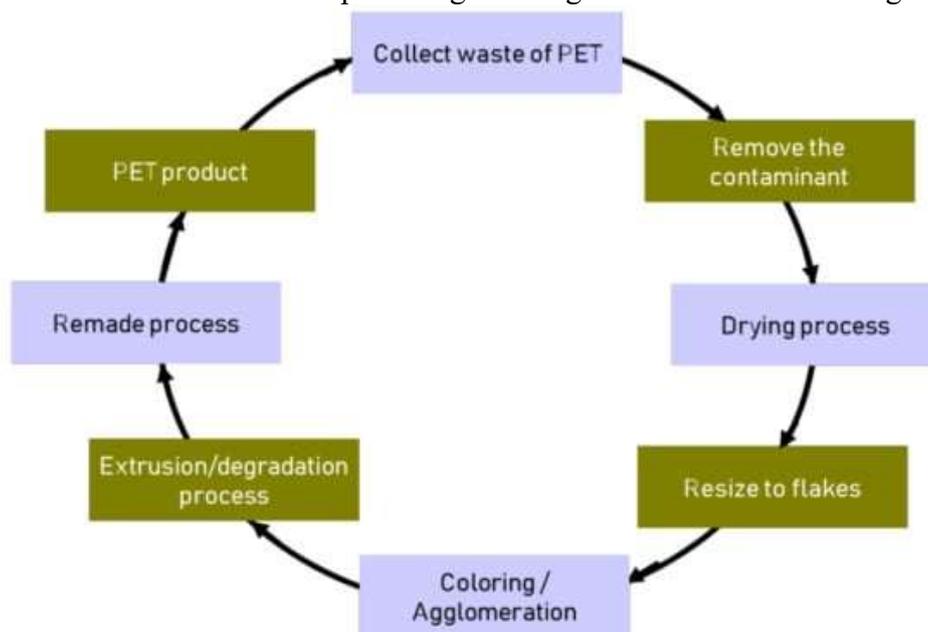


Figure 3: Scheme of the conventional mechanical process of PET recycling.

3.1 Mechanical Recycling

Mechanical recycling can be a very profitable process and is already widely used; nevertheless, degradation must be kept under control during the process. In order to prevent thermo, oxidative degradation and keep mechanical properties, the extrusion temperature should be optimized, residence time should be controlled, and the material should be properly dried[19].

3.2 Chemical Recycling

Chemical recycling breaks down the PET into its monomers which can then be purified and re, polymerized into high, quality polyester. This technology has the potential to give a material that is as good as a virgin PET one but at present, it is hampered by high energy consumption and cost[20].

3.3 Performance Restoration Strategies

Strategies such as solid-state polymerization, chain extenders, and blending with virgin PET are used to restore molecular weight and improve mechanical reliability. These approaches are critical for enabling rPET use in safety-critical webbing applications.

Despite these challenges, experimental studies have demonstrated that high-quality recycled polyamide fibers can achieve tensile strength and abrasion resistance comparable to virgin materials when strict control over feedstock quality, moisture content, and processing conditions is maintained[21]. However, the hygroscopic nature of polyamides remains a critical concern, as moisture absorption during storage and service can lead to hydrolytic degradation and changes in elongation behavior. Consequently, recycled polyamides are currently more prevalent in non-structural automotive textiles, while their use in seat-belt webbing continues to be evaluated under controlled and highly regulated conditions.

4. Bio-Based Polymers and Renewable Feedstocks

The use of bio-based polyamides in seat-belt webbing offers several sustainability advantages, including reduced greenhouse gas emissions and improved resource renewability. However, their widespread adoption is constrained by higher material costs, limited production capacity, and sensitivity to agricultural feedstock availability[22]. Additionally, comprehensive long-term durability data under automotive service conditions remain limited, necessitating extensive testing to assess fatigue resistance, creep behavior, and environmental ageing performance before deployment in safety-critical systems[23].

Biodegradable polymers such as polylactic acid (PLA) have also been investigated as potential sustainable alternatives for automotive textiles. PLA offers advantages in terms of renewable sourcing and end-of-life biodegradability. However, its relatively low thermal stability, poor hydrolytic resistance, and limited fatigue performance significantly restrict its suitability for seat-belt webbing, which must withstand high temperatures, cyclic loading, and long-term mechanical stress[24]. Consequently, biodegradable polymers are currently more suitable for non-load-bearing automotive components rather than primary restraint systems. Nonetheless, its fairly low heat resistance, bad hydrolytic resistance, and short fatigue life severely limit its application for seat, belt webbing, which is required to resist high temperatures, cyclic loading, and long, term mechanical stress. Therefore, at present, biodegradable polymers are more apt to be used for non, load, bearing automotive parts than for primary restraint systems.

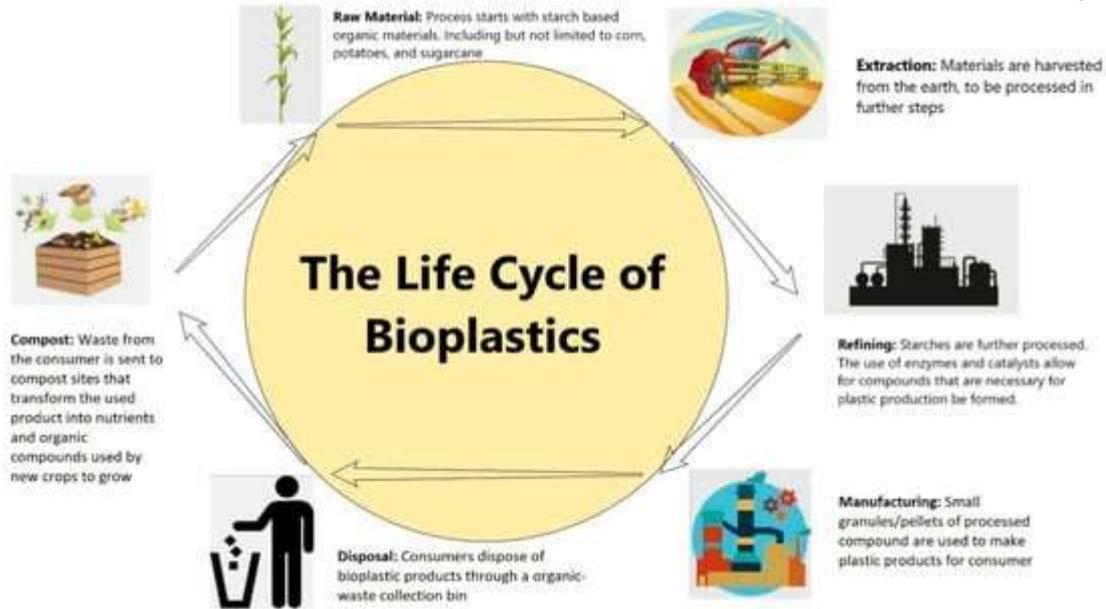


Figure 4. Life cycle of bioplastics[25]

5. Hybrid and Composite Material Approaches

Hybrid and composite material systems represent an effective way to reconcile sustainable development goals with the highly demanding mechanical properties of seat, belt webbings. In these systems, fibers made from recycled polyester or polyamide can be blended with bio, based polymers, virgin reinforcement fibers, or even high, performance materials that would make up for any drop in molecular weight or fatigue resistance resulting from recycling. By adjusting the material composition and fabric layout, hybrid systems are able to deliver performances at the same level as traditional webbings while still maintaining a large percentage of sustainable content[26].

On a fabric scale, the combination of weave density, yarn crimp, and edge reinforcement plays a significant role in increasing tensile strength and energy absorption. A controlled yarn crimp enables the yarns to be gradually straightened as a load is applied, thus elongation during impact is controlled. On the other hand, reinforced selvage constructions increase the abrasion resistance of contact points that are under critical stresses. Further, surface treatments and coatings may offer great protection against UV radiation, water penetration, and microbial attack, hence they can prolong the service life in a car environment that is always a challenge[27].

Hybrid material systems do offer some benefits but also come with challenges from the standpoint of manufacturing, quality control, and recycling at the end, of, life stage. Having different material types present can make the recycling process more difficult and lower the efficiency of material recovery. Consequently, it is vital to take great care when selecting compatible materials and applying design, for, recycling concepts in order to make sure that hybrids contribute to...contribute positively to long-term sustainability goals[28].

6. Degradation Mechanisms in Recycled and Bio-Based Fibers

Understanding the degradation mechanisms of the seat belt material is crucial for the reliability assessment of green/sustainable materials on the long run. Among the polymer fibers, polyester made from recycled materials is very vulnerable to both thermal and oxidative deterioration, which happen during the melting process. These processes cause damage to the polymer chains resulting in a lowering of the molecular weight and changes in the crystalline morphology. The changes at the micro, level result in a fall of the tensile strength, change in elongation behavior, and decrease in fatigue resistance[29].

Besides, recycled polyamides are more prone to hydrolytic degradation because they are hygroscopic. The moisture taken during storage, processing, or service accelerates the cleavage of the chain at high temperature which in turn results in a further loss of the mechanical properties. Depending on their chemical composition and the additives used, bio, based polymers can also be degraded through heat instability, UV exposure and sensitivity to environmental factors[30]. During the vehicle's lifetime, the environmental exposure will make the degradation even worse. UV light can cause photo, oxidation processes to be initiated, high temperature can speed up thermal ageing, and continuous load cycles can lead to fatigue damage and micro, cracks. Therefore, a thorough knowledge of degradation mechanisms is necessary for the prediction of service life as well as safety regulation compliance.

6.1 Influence of Weaving Architecture and Webbing Design

The performance of seat, belt webbing is not only dependent on the inherent properties of the fibers that make up the yarn but also on the weaving architecture and the overall fabric design. Several fabric parameters such as the type of weave, linear density of the yarn, yarn crimp, pick density, webbing width, and the construction of the edges will have a considerable effect on the tensile behavior, elongation characteristics, abrasion resistance, and energy absorption capacity of the webbing. In the case of materials that are sustainable and recycled, the optimization of the weaving architecture becomes highly desirable in order to be able to make up for the slight decrease of fiber, level mechanical properties[31].

The regulated yarn crimp within the woven structure is a significant factor in determining the elongation behavior. When a tensile load is applied, the crimped yarns are gradually straightened, which allows for controlled elongation and dissipation of energy during a collision event. If the crimp is too much, the elongation may become too large, and if there is not enough crimp, a high peak load will be transmitted to the occupant. Consequently, it is necessary to accurately regulate the crimp geometry in order to satisfy the requirements of the regulations[32].

Edge reinforcement is another important aspect of the design, as the edges of the seat, belt webbing are highly vulnerable to wear and tear because they are constantly rubbed against hardware parts. To increase the durability of the fabric and avoid early breakage, reinforced selvage constructions, more yarn per unit length at the edges, and different weaving patterns are frequently used[33]. Treatment of the fabric with a coating of resin and changes to the surface are some of the finishing operations that help to make the fabric more resistant to ultraviolet rays, penetration of water, and attack by microorganisms. By means of thorough fabric, level tailoring, areas where fibers have been cropped can be successfully used in safety, critical seat, belt webbings without performance being sacrificed.

7. Manufacturing Challenges and Process Optimization

Recycling and bio, based materials for the production of seat, belt webbing may cause the process to be unstable, resulting in quality inconsistencies and a lack of readiness for mass production. It is known that compared to virgin fibers, recycled fibers generally have a greater variability in molecular weight, filament diameter, tensile strength, and thermal behavior. The negative impacts of this variability on spinning stability, weaving efficiency, and the quality of the final webbing may become very significant unless proper control is exercised.

When it comes to fiber spinning and drawing, a recycling polymer is more time and parameter sensitive thus requires more precise control of extrusion temperature, draw ratio, and residence time to minimize degradation and achieve consistent orientation. With respect to weaving, the inconsistencies of yarn strength and elongation will cause yarn breakage to increase, thus resulting in more stoppages and less productivity. Therefore, when handling sustainable fibers, it is necessary to carefully optimize loom tension, take, up speed, and the state of the environment.

Moreover, finishing processes such as dyeing, heat setting, and coating might also be altered because of differences in surface chemistry and thermal sensitivity caused by recycled and bio, based materials. In terms of industry goals, scaling up is still the main issue. Even though pilot, scale experiments have proved that

sustainable seat, belt webbings are possible, to produce consistent quality on high output volumes advanced process monitoring, inline quality control systems, and efficient supply chain management are required [34].

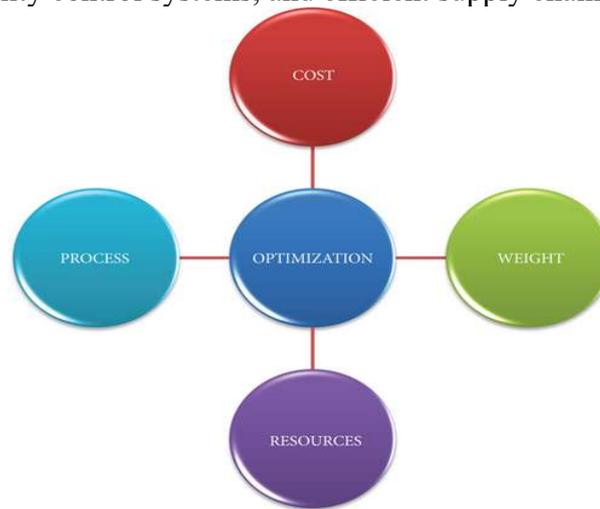


Figure 5: Different applications of optimization

As illustrated in Figure 5, resource, weight, cost, and process are chosen for the optimization ways. The current optimization problem identified in the material extrusion process is as follows.

7.1 Testing, Standards, and Certification Requirements

Seat belt webbing has to be safe and therefore it is strongly regulated to ensure it can protect the car occupants in different situations. Certification testing normally consists of tensile strength testing, elongation measurement under specified loads, abrasion resistance evaluation, and environmental aging tests with exposure to heat, ultraviolet radiation, humidity, and chemicals. In the case of eco, friendly materials, the testing may have to be carried out for batch, to, batch variability, long, term durability, and resistance to degradation mechanisms specific to recycled or bio, based polymers[35].

Protocols of accelerated ageing which include the combination of mechanical fatigue, thermal cycling, and environmental exposure are quite essential for the prediction of long, term performance of green seat belt webbings. Current laws focus almost solely on the performance outcomes and are largely indifferent to the type of material used, however, the lack of standardized guidelines specifically for recycled materials is an obstacle to their widespread use. Testing frameworks development could lead to increased confidence and regulatory acceptance of sustainable seat, belt materials if they are introduced as supplemental tools[36].

8. Life-Cycle Assessment and Environmental Impact

Life, cycle assessment (LCA) is a perfect tool for looking at how a new seat, belt webbing made from sustainable materials is really good or not when you take the whole life cycle into consideration i.e. from the extraction of raw materials to the end, of, life management.

Several LCA analyses have indicated that fibers made from recycled polyester can lead to a 30-50% reduction in energy consumption and greenhouse gas emissions as compared to virgin polyester, the exact figures depending on the recycling efficiency and the type of energy used. These results mainly come from the fact that less energy is used when the production of the polymer from the chemical raw materials and the extraction of the latter are avoided[37].

Nonetheless, the total environmental impact of a sustainable seat, belt webbing still depends on a number of factors such as the distances for transportation, efficiency of processing, the use of additives, and the scenarios of end, of, life. Mechanical recycling usually consumes less energy but might lead to the lowering of material quality while chemical recycling can reestablish polymer properties at the cost of greater energy consumption

(Awaja and Pavel, 2005). Polymers that are bio, based have the benefit of being renewable source, wise, however, their green advantages should be weighed when considering land utilization, farming inputs, and the rivalry with food stuffs[38].

Therefore, the choice of materials for the manufacturing of sustainable seat, belt webbing ought to be driven by thorough life, cycle assessments that consider not only environmental benefits but also technical performance, safety compliance, and economic feasibility.

9. Emerging Technologies and Research Gaps

Despite the fact that there has been a lot of work done on sustainable and recycled materials for seat, belt webbing, there are still a few technological gaps and challenges that have not been solved yet. A major problem is the variability of recycled feedstocks. Polymer waste from post, consumer sources generally has inconsistent molecular weight, contamination levels, and thermal history, which in turn can affect fiber properties and lead to less reproducibility of large, scale manufacturing. Such variability is extremely sensitive in applications that are safety, critical like a seat, belt webbing, where consistency and reliability are the key factors.

Some innovative methods of processing are being developed to solve these difficulties by enhancing polymer quality during recycling. Reactive extrusion is increasingly recognized as a new technique that allows molecular weight restoration through controlled chemical reactions during melt processing. This method makes it possible to carry out compounding, chain extension, and stabilization all at once, thus decreasing the number of processing steps and upgrading material performance). Nevertheless, fine, tuning the behavior of the reactants and the compatibility of the additives is, to a large extent, still an issue to be resolved by researchers.

Besides this, there is the development of process optimization and control methodologies based on real, time data acquisition and machine learning technologies. These techniques provide efficacious monitoring and control to spinning, drawing, and weaving processes, which basically means manufacturers can manage changes in recycled polymer properties and thus produce more consistent products. Initial research has shown that these methods can indeed lead to increased efficiency. However, at the present time, safety textiles produced at an industrial scale are still very much a limited avenue of implementation.

Potentially, nanocomposite technologies could be another line of work to consider seriously. For example, very small amounts of nanofillers like nanoclays, graphene, or silica nanoparticles have been found to significantly improve the tensile strength, thermal stability, and barrier properties of polymer fibers[39]. It is important, however, that issues related to recyclability, nanoparticle dispersion, health risks, and long, term durability be thoroughly investigated before these materials become part of automotive restraint systems.

In general, there is a huge lack of reliable long, term performance data obtained in real, life conditions, which together with the absence of materials and methods standards specific to recycled products and poor understanding of the degradation of materials subjected to combined mechanical and environmental loading, makes a list of major research gaps that call for a systematic study.

10. Conclusion

Sustainable and recycled materials used in seat, belt webbing can significantly reduce the environmental impact of automotive safety systems and at the same time help to achieve the global sustainability goals. Recycled polyester and recycled polyamides are currently the most viable options to replace conventional virgin polymers as they have well, established recycling systems and their mechanical performance is equally good. Bio, based polymers and hybrid material systems offer further attractive possibilities, but at present these are only options as they are constrained by high costs, limited availability and uncertain durability.

The main problems of sustainable seat, belt webbing materials are the inconsistency of the materials, wear and tear during recycling, very strict safety certification requirements and scarcity of in, use data confirming long, term durability. These problems can be solved by employing an integrated approach that includes enhancement of polymer recycling technologies, optimization of fiber processing, innovation in textile design and development of standardized testing procedures.

By proper cooperative work of universities, raw material producers, textile makers, car manufacturers, and governing authorities it is possible to allow sustainable seat, belt webbing to deliver significant environmental benefits without negatively affecting the safety level of occupants. Safety, compliant & life, cycle, oriented design, sustainable seat, belt webbing may become an indispensable element in the future of green automotive technology.

11. Future Research Directions

More integrated material process performances frameworks are needed to facilitate a dependable implementation of sustainable materials in seat, belt webbing without any trade, off in safety. One of the key research topics should be the development of advanced recycling techniques that can maintain or regenerate the polymer's molecular weight and microstructural features. Besides chemical recycling improvements, energy, saving solid, state polymerization comes up as a good option for obtaining recycled polymers with properties on a par with virgin ones.

The extensive studies should also take the stages of the combined effects of fatigue loading, creep deformation, thermal ageing, ultraviolet exposure, and humidity into consideration for the more exact prediction of long, term performance under actual automotive service conditions. Currently, many certification methods are geared toward short, term performance indicators and, therefore, might not really demonstrate the time, dependent degradation behaviour in recycled and bio, based fibers.

On a textile design level, next research should look into sophisticated weaving structures and functional treatments that are specially made for recycled fibers. By the proper placement of yarn in the fabric, varying fabric density visually, and using very strong selvage designs, it may be possible to profoundly improve energy absorption and abrasion resistance thus compensating the application of the fibers which are not so good in terms of properties at a micro, level.

Alongside it, the formulation of fixed testing and certification protocols that focus on recycled and bio, based materials will undoubtedly serve as a bridge to the industrial sector and thus significantly smooth out the pathway of release for such materials. The existence of such standardization mechanisms will allow clear positioning of qualification criteria and will certainly help in resolving the problem of uncertainty among automotive manufacturers. Incorporating life, cycle assessment at the earliest stage of material selection and design decision, making should also be given the main priority in order to achieve real sustainability gains.

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