

Recycling Polyphenylene Sulfide (PPS): A Comprehensive Review of Mechanical, Thermal and Physical Properties for Aerospace Engineering Applications

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ABSTRACT

Polyphenylene Sulfide (PPS) is a high-performance thermoplastic widely utilized in aerospace applications due to its exceptional mechanical, thermal, and chemical resistance properties. However, the increasing demand for PPS-based materials has led to significant waste generation, posing sustainability challenges. This review explores the feasibility of PPS recycling for aerospace applications, addressing key knowledge gaps, limitations, and environmental implications. Despite advancements in mechanical and chemical recycling techniques, challenges remain in maintaining the mechanical integrity of recycled PPS, particularly in fiber-reinforced composites. Polymer degradation, chain scission, and contamination affect recycled PPS properties, reducing tensile strength, impact resistance, and crystallinity, which limits its application in load-bearing aerospace components. Furthermore, the lack of standardized testing and certification processes for recycled PPS in aerospace remains a critical gap that hinders widespread adoption. Recycling PPS presents sustainability benefits, particularly in reducing polymer waste, minimizing carbon emissions, and promoting circular economy initiatives. Mechanical recycling offers cost-effective material recovery but results in compromised mechanical performance due to thermal and shear degradation. Chemical recycling, while capable of restoring polymer purity, is hindered by high energy demands and the use of hazardous chemicals. Innovations in reinforcement strategies, such as the integration of glass or carbon fibers, have shown potential in restoring mechanical properties, making recycled PPS suitable for non-structural aerospace applications like aircraft interiors, ventilation systems, and protective enclosures. This review emphasizes the need for further research into optimizing recycling techniques, improving process scalability, and establishing regulatory frameworks to ensure the structural reliability of recycled PPS in aerospace applications.

Keywords: Recycled PPS; properties; aerospace; sustainability

INTRODUCTION

Recently, there were numerous types of engineering thermoplastics such as polyphenylene sulfide (PPS), polyether-ether-ketone (PEEK), polyaryl-ether-ketone (PAEK) and polyether-imide (PEI) that evolve and being implemented widely throughout manufacturing industries such as aerospace, energy, and automotive industries. These thermoplastics possess strong mechanical performances despite their lightweight properties. For instance, they are capable of withstanding high load due to their outstanding mechanical properties. Specifically, polyphenylene sulfide (PPS) plays a crucial role in aerospace industries as it is known as high-efficiency material that exhibits excellent mechanical, thermal and physical properties due to its polymeric structure (Montagna et al. 2022).

PPS is a well-known high-performance thermoplastic which contributes significantly to the aerospace industry because of its good dimensional stability, tensile and modulus strength, fatigue resistance, flame resistance and resistance towards solvents, chemicals, and extreme high temperature. In terms of its molecular structure, PPS is formed by arranging the sulphur atom and aromatic rings which makes it unique and categorized as semicrystalline polymer. Additionally, PPS is widely implemented in the aerospace industry for structural components. As a replacement of metals, PPS has proved to contribute to aerospace application in terms of weight reduction and fuel efficiency. Due to its low electrical conductivity, PPS acts as an electrical insulator to ensure reliability and safety of the electrical system for the aircraft. Besides the aerospace industry, PPS also being applied in other industries such as automotive industry, healthcare industry, electrical and electronics industry etc. Furthermore, PPS can be served as a fundamental or blending material to fabricate different kinds of products that suit the best for each industry. That includes engine and electrical components, PCB circuit board, structural parts, switches and relays and piping (Montagna et al. 2022).

Moreover, the growth of the aerospace industry and the improvement of aircraft components are significantly influenced by advancements in lightweight materials and related technologies, particularly in the fast assembly of structures. "Lightweight structures" refer to materials designed to minimize weight while optimizing their use of resources, requiring minimal energy for construction, and achieving economical spans. The integration of lightweight materials into engineering coincided with the development of more fuel-efficient

transportation methods. Aerospace manufacturers in advanced industries are actively working to reduce energy consumption by adopting lighter materials such as lightweight metals, polymers, and composites. These materials enable compliance with strict weight-reduction standards for aeronautical applications. Additionally, sustainability plays a crucial role, often focusing on material recyclability, emission reductions in aircraft, and life cycle assessment with analysis. Therefore, PPS is chosen to be a fundamental material in aerospace engineering by combining its structure with reinforcement and form a polymer blend which ultimately provides a tough, light and high thermal and chemical resistance. For example, PPS composites are used in various aircraft components, including ailerons, rudders, flaps, spoilers, elevators, vertical and horizontal stabilizers, wing panels (both leading and trailing edges), landing gear doors, nacelles, flap rail fairings, and wing boxes. Notably, the A380 is the first aircraft to feature a central wing box constructed entirely from composite material (Montagna et al. 2022).

Furthermore, the rising demand for engineering thermoplastics, particularly PPS, has resulted in significant waste accumulation throughout manufacturing and product life cycles. Due to the sophisticated technology and complex processing involved in producing PPS-based composites and blends, recycling is often challenging, leading to disposal through landfilling or incineration. However, increasing environmental concerns have encouraged industries relying on these materials to consider recycling, not only to reduce waste but also to recover valuable resources. Presently, mechanical and thermal recycling methods provide a sustainable and economically viable solution for managing PPS-based waste. These approaches not only help mitigate environmental impacts by diverting waste from landfills and incineration but also allow for reintegration into manufacturing or repurpose in different industries, especially in aerospace industry.

This paper illustrates numerous outcomes that are highly relevant to recycled PPS, including its recycling method, recyclability, overall properties upon recycled, applications, challenges towards sustainability etc. For example, there are several recycling methods such as mechanical and chemical recycling methods, followed by the emerging techniques that contribute to the effectiveness of PPS recyclability. Undoubtedly, this review discusses significant and specific fields in terms of PPS with its recyclability that helps in aerospace industry application (Chen et al. 2021).

RECYCLING METHODS FOR PPS IN AEROSPACE APPLICATION

MECHANICAL RECYCLING

Mechanical recycling is a widely adopted method for recycling thermoplastics, including PPS, which can be applied similarly to other thermoplastics like PP, PET, and PVC. This process involves several stages to transform waste PPS into reusable material.

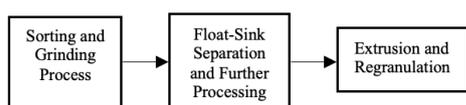


FIGURE 1. Flow chart for mechanical recycling of PPS (dos Santos et al. 2024)

By referring to Figure 1, the process starts with sorting and grinding. PPS is sorted and transported via a conveyor belt to a primary shredder, where it is broken down into fist-sized pieces. These fragments are stored in a silo before undergoing an initial washing stage to remove contaminants like rocks and metals using a rotating drum washer with water flow. Then it follows by shredding and washing. The larger fragments undergo a secondary shredding process, reducing them into flakes (1-12 mm). These flakes are washed again to remove organic residues before proceeding with a float-sink separation system. The second phase is a float-sink method that separates polymers based on the density. PPS, PP, and PE float, while denser materials like PET and PVC sink. This process is cost-effective and widely used for sorting plastic flakes. The floating fraction, containing PPS, is dried and processed through a wind sifter to separate materials based on mass. The heavier fraction is suitable for reuse, while the lighter fraction undergoes regranulation through extrusion with melt filtration (Uzosike et al. 2023).



FIGURE 2. Mechanical Recycling Flow of Thermoplastic Composites (dos Santos et al. 2024)

The final step involves extruding the sorted PPS flakes into granules or pellets. This process uses heat and rotating screws to soften the polymer, which is then shaped into a continuous extruded. However, extrusion can lead to molecular transformations such as thermo-oxidative degradation and shear-induced chain scission, reducing the material's mechanical properties. The counteract property degradation, fillers like glass fibers or calcium carbonate can be added to enhance mechanical properties such as Young's modulus and impact strength. Mechanical recycling of PPS is a viable method for producing secondary raw materials suitable for aerospace applications. While it offers cost-effective and scalable recycling, careful management of extrusion conditions and the use of fillers are crucial to maintaining the material's performance (Uzosike et al. 2023). Figure 2 shows the summary of the mechanical recycling method.

CHEMICAL RECYCLING

Chemical recycling is an effective process that involves breaking down waste composites by dissolving them in chemical solutions, such as acids or bases, depending on the composition of the polymer matrix. During this procedure, the recovered long fibers undergo a thorough washing to eliminate any remaining surface contaminants. Compared to mechanical and thermal recycling techniques, chemical recycling achieves a higher resin decomposition rate. Chemical recycling method works by degrading the polymer matrix within the composite, converting it into chemicals that can either be repurposed as fuel or used to synthesize new polymers. This approach allows for the recovery of both the polymer and valuable reinforcing materials and fillers from thermoset composites. To further optimize resin degradation, advanced techniques such as solvolysis or hydrolysis are employed (J. Li et al. 2020).

To further illustrate the solvolysis, it is a technique that being categorized into two types based on temperature and pressure conditions: high-temperature and high-pressure (HTP) solvolysis, which operates above 200°C, and low-temperature and low-pressure (LTP) solvolysis, conducted below 200°C. However, the most widely used method for chemical recycling is low temperature solvolysis. This technique utilizes reactive solvents to break the chemical bonds within the polymer matrix, effectively separating it from the carbon fibers (CF). Through this process, clean fibers and fillers can be recovered, while the decomposed resin can be repurposed as feedstock for producing new resin. However, solvolysis might induce several drawbacks due to its tendency for creating harmful environment (Wang et al. 2021).

In short, chemical recycling has the capability to generate high-quality recycled carbon fibers, but this is only achievable under specific conditions and with the use of hazardous chemicals. Therefore, alternative recycling methods are necessary ones that can maintain excellent fiber quality, accommodate a wide range of composites, and remain environmentally sustainable. One major drawback of solvolysis is that its efficiency depends on the type of resin being processed, making it essential to pre-sort composite materials. As a result, this method is well-suited for handling production waste with well-defined material properties but poses significant challenges when dealing with mixed post-consumer composite waste. Additionally, the required reactors can be costly, as they must be designed to withstand extreme temperatures, high pressure, and corrosion caused by aggressive chemical solvents. Furthermore, the process demands substantial energy input, making its environmental impact less favorable compared to mechanical recycling, although it is like pyrolysis in terms of sustainability recorded (Wang et al. 2021).

COMPARATIVE ANALYSIS

Advancements in recycling technologies have enabled recycled PPS to retain mechanical properties similar to its virgin counterpart. For example, Toray Industries has developed a method for recycling glass fiber-reinforced PPS (PPS-GFRP), maintaining structural integrity even when incorporating over 50% recycled content. Additionally, this approach reduces CO₂ emissions by approximately 40%. Likewise, Polyplastics has introduced a 40% glass-filled recycled PPS that adheres to the same quality standards as virgin materials, contributing to sustainability by lowering waste and carbon emissions (Long, 2020).

The use of recycled PPS can be a cost-effective alternative due to savings on raw materials and lower energy consumption during manufacturing. However, its overall economic advantage depends on factors such as processing complexity, quality of the recycled material, and market demand. While recycled PPS offers financial benefits, additional costs may arise from material collection, sorting, and reprocessing. The feasibility of large-scale recycled PPS production is influenced by factors such as the availability of recyclable PPS waste, advancements in recycling processes, and market infrastructure. Companies like Toray and Polyplastics are making efforts to improve the scalability of recycled PPS by investing in advanced recycling technologies. For instance, Polyplastics has implemented a post-industrial recycling system to ensure a consistent supply of high-quality recycled PPS for various applications. With

continued improvements in recycling efficiency and infrastructure, the potential for widespread adoption of recycled PPS is expected to grow (Long, 2020).

In conclusion, innovations in recycling technology have significantly enhanced the performance of recycled PPS, making it comparable to virgin PPS while offering sustainability advantages. As technological developments progress, the cost-effectiveness and scalability of recycled PPS will likely improve, making it a viable option for a range of industries (Long, 2020).

MECHANICAL PROPERTIES OF RECYCLED PPS

Recycled PPS demonstrates a key finding in terms of its performance and accessibility to aerospace applications. Therefore, its mechanical properties are a major concern to assess the impact towards aerospace industry. Recycled PPS, which is considered a thermoplastic, possesses similar properties like any other thermoplastic. Momanyi et al. discovered that the tensile strength of recycled PP is lower than virgin PP by 33% to 38.2% at different temperatures as shown in Figure 3 (Momanyi et al. 2019).

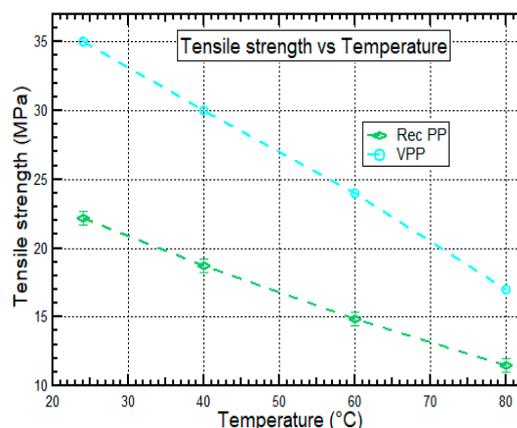


FIGURE 3. Tensile Strength vs Temperature (Momanyi et al. 2019)

The reduction in tensile strength resulted from structural transitions that led to increased molecular mobility within the crystalline phase. This change was driven by a decrease in the crystals' shear strength when exposed to high temperatures. Recycled PP also naturally deteriorates over time due to chain scission and thermo-mechanical degradation. This degradation occurs because of exposure to high temperatures, oxidation, and mechanical shearing during processing (Momanyi et al. 2019).

Furthermore, when the concentration of recycled polypropylene in the mixture increased, its impact resistance gradually declined. Specifically, the impact

resistance of PPr100 was 86% lower than that of PPv100, with values of 49.53 kJ/m² for virgin polypropylene and 6.67 kJ/m² for the recycled variant as shown in Table 1. As the material degrades during the recycling process due to exposure to high temperatures and shear forces, this could explain the decline in impact resistance values (Sharif et al. 2024).

TABLE 1. Impact Resistance of PP Samples (Sharif et al. 2024)

| Sample | Impact Resistance |
|--------|-------------------|
| PPv100 | 49.53 ± 3.49 |
| PPr10 | 28.58 ± 11.75 |
| PPr20 | 16.51 ± 3.49 |
| PPr30 | 13.34 ± 2.22 |
| PPr100 | 6.67 ± 1.91 |

Besides, the compressive strength of rPPS with different added chromophore groups are summarized as Table 2. It is observed that compressive strength of rPPS ranges from 70.4 to 85.4 MPa. This implies that the large chromophore groups within the main PPS chain hinder molecular chain mobility, increasing rigidity and ultimately enhancing its mechanical properties (Sharif et al. 2024).

In aerospace applications, both virgin and recycled Polyphenylene Sulfide (PPS) offer unique advantages, but their suitability depends on performance requirements. Virgin PPS is preferred for critical components due to its superior mechanical strength, thermal stability, and chemical resistance, making it ideal for structural parts, high-temperature electrical insulation, and fuel system components. In contrast, recycled PPS, while more cost-effective and sustainable, may exhibit slight reductions in mechanical properties due to polymer degradation. As a result, it is typically used in non-critical applications such as interior cabin panels, protective covers, and secondary structural components (Montagna et al. 2022).

TABLE 2. Compressive Strength of rPPS (Sharif et al. 2024)

| Product | Compressive Strength (MPa) |
|------------|----------------------------|
| PPS | 78.9 |
| PPS-P3RKSb | 85.4 |
| PPS-PRKSb | 77.8 |
| PPS-PR32Sb | 83.5 |
| PPS-PB6Sb | 83.4 |
| PPS-PR1Sa | 70.7 |
| PPS-PR1Sb | 73.3 |
| PPS-PR1Sc | 75.4 |

Additionally, performance of recycled PPS may deteriorate due to material degradation after recycling. As a result, it is essential to introduce reinforcement such as filler or additive for producing a strong composite. Kadhim et al. (2023) conducted a series of experiments by adding 40% of glass fibres into PPS. It was found that the tensile

strength of PPS/GF is higher than that of virgin PPS under various temperatures. This was due to the varying shrinkage rates between the matrix and the fibres as glass fibres remain unaffected by temperature reduction. As a result, they tend to slide and hinder the matrix from shrinking and the molecular chains from properly aligning as the temperature drops.

For PPS matrices reinforced with glass fibres (PPS/GF), structural changes in the material can be observed, like those seen with carbon fibre reinforcement, as highlighted in the research by Wang et al. These studies provide insights into the crystallization and melting behaviour of PPS/GF (Kadhim et al. 2023). Additionally, an analysis by Zuo et al. (2019) comparing PPS/GF composites with and without thermal aging. Their findings indicate that crystalline increases with aging but eventually declines. Specifically, virgin PPS/GF exhibited 44.2% crystallinity, which increased to 45% after 20 hours, 55.8% at 96 hours (the peak value), then decreased to 52.9% at 144 hours and further dropped to 36.6% after 1080 hours. Another study by Zhao et al. (2019) focused on PPS/GF composites with a high glass fibre content, demonstrating distinct trans crystallinity characteristics.

Moreover, Batista et al. (2019) investigated the effects of temperature, humidity, and UV radiation on PPS/CF composites using water immersion and UV climate chamber techniques. The composites, produced via hot compression molding at 280–290°C, underwent artificial aging (200, 600, and 1200 hours) following ASTM G 154. Results showed that short-term UV exposure enhanced compression strength due to crosslinking, while prolonged exposure led to mechanical degradation from photolysis, photo-oxidation, and embrittlement. Dynamic mechanical analysis (DMA) indicated increased glass transition temperature (T_g) with longer exposure, reducing molecular mobility. Additionally, water absorption increased with temperature, accelerating the diffusion process.

PHYSICAL PROPERTIES OF RECYCLED PPS

Undoubtedly, recycling PPS may impact the physical properties of PPS in terms of density and trans crystallinity. This statement is further agreed by Jiun et al. who conducted research to study the effects of recycling cycle on used thermoplastic polymer and thermoplastic elastomer polymer. Figure 4 illustrates how the number of recycling cycles affects the density of both thermoplastic polymers and thermoplastic elastomers. The data indicates a declining trend in thermoplastic polymer density as recycling cycles increase, aligning with previous studies. A density reduction of approximately 2.1% was observed between the first and fifth recycling cycles. This decrease

is attributed to polymer chain scission caused by crushing and melting during recycling. Additionally, thermal degradation weakens intermolecular forces, while smaller polymer fragments formed through chain scission may volatilize and escape during the melting process. Furthermore, repeated recycling leads to reduced crystallinity, which is also linked to chain scission effects (Sharif et al. 2024).

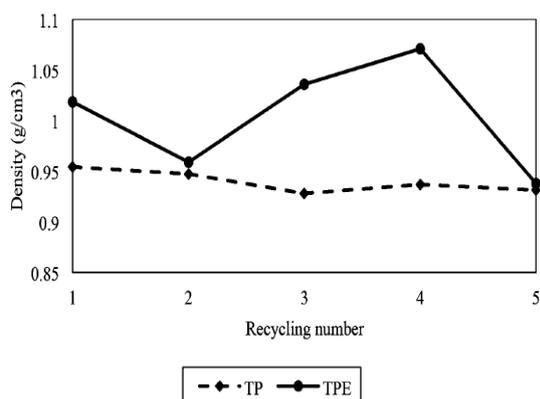


FIGURE 4. Density vs Recycling Number of TP and TPE (Jiun et al. 2016)

Nevertheless, contamination plays a crucial role in determining the quality and mechanical properties of recycled materials. The formation of polymer blends from inseparable multilayers, along with thermo-mechanical degradation during mechanical recycling, makes it difficult to predict the properties of the secondary material. As a result, it may not meet the specifications required for certain applications, particularly in processes like casting, where sufficient melting strength is essential but often compromised during recycling. According to research by Seier et al. (2024), contaminated particles with different sizes will affect the mechanical performance of thermoplastic. According to Figure 5, morphological structure changed as the particle size became larger. This is because particle size and distribution are strongly influenced by the polarity differences and viscosity ratio of the components. These factors create favorable conditions for developing a homogeneous structure in polyolefin-based blends. So, recycled PPS will induce higher material brittleness with lower quality as recycling process is contaminated with some foreign particles with various sizes compared to virgin PPS.

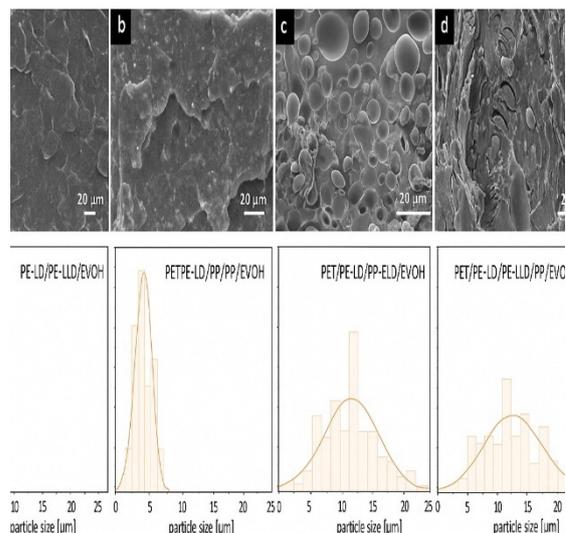


FIGURE 5. Recyclate morphology of common post-consumer packaging blends comprising (a) PE-LD/PE-LLD/EVOH, (b) PE-LD/PE-LLD/PP/EVOH, (c) PET/PE-LD/PE-LLD/EVOH, (d) PET/PE-LD/PE-LLD/PP/EVOH demonstrated using scanning electron micrographs and particle size distribution curves. (Seier et al. 2024)

THERMAL PROPERTIES OF RECYCLED PPS

The alteration of thermal properties of PPS after recycling becomes crucial as it brings impact on mechanical properties too. For instance, recycled PPS exhibit lower glass transition temperature, than virgin ones with lower melting temperature. Zdiri et al. and Shayuti et al. conducted similar experiments and found that the melting point of virgin polypropylene (PP) was 166.3°C and 163.3°C, respectively. The glass transition temperature (T_g) of recycled PP was approximately 12.9% lower than that of virgin PP due to various factors, including reprocessing conditions, thermal history, imperfections in crystal formation, polymer chain degradation during melting, and other structural changes. The broad melting peak observed for both recycled and virgin PP, as shown in Figure 2, suggests the coexistence of different crystalline structures and a wide distribution of crystallite block lengths in both the soft (amorphous, atactic PP) and hard (crystalline, isotactic PP) phases. This broad peak also results from the melting of crystallized regions formed through the co-crystallization of stereo-regular sequences (Sharif et al. 2024).

Furthermore, recycling has a significant effect on the thermal conductivity and heat deflection temperature (HDT) of Polyphenylene Sulfide (PPS) due to polymer breakdown, contamination, and structural modifications occurring during reprocessing. These changes influence the material's ability to conduct heat efficiently and

maintain stability under high temperatures. One of the key impacts of recycling is the decline in thermal conductivity. Compared to virgin PPS, recycled PPS generally exhibits reduced heat transfer capabilities due to polymer chain scission and increased void formation. The repeated heating and cooling cycles during recycling introduce structural imperfections, disrupting the material's ability to conduct heat effectively. In fiber-reinforced PPS composites, such as PPS reinforced with glass fibers (PPS/GF) or carbon fibers (PPS/CF), the redistribution or breakage of fillers further contributes to reduced thermal conductivity by affecting the continuity of heat dissipation pathways (Hamdan et al. 2022).

Moreover, the heat deflection temperature (HDT) of PPS decreases after recycling due to molecular changes. Factors such as polymer chain degradation, reduced molecular weight, and lower crystallinity weaken the material's resistance to heat and mechanical stress, making it more susceptible to deformation at elevated temperatures. The presence of impurities and oxidation from repeated processing further weakens intermolecular forces, resulting in reduced stiffness and thermal stability. In cases where reinforcement fillers like glass or carbon fibers are included, their degradation or uneven distribution within the polymer matrix can also impact on HDT (Hamdan et al. 2022).

Besides, recycled Polyphenylene Sulfide (PPS) often experiences a decline in thermal properties due to polymer degradation, reduced crystallinity, and structural defects caused by repeated processing. However, several techniques can be applied to restore and improve its thermal conductivity and heat resistance, ensuring it remains suitable for high-performance applications. One effective method is annealing, which involves controlled heating followed by gradual cooling. This process allows polymer chains to rearrange and form a more ordered crystalline structure, thereby increasing crystallinity and thermal stability. As a result, annealing enhances heat deflection temperature (HDT) and improves the material's ability to withstand high temperatures without deformation (Costa et al. 2023).

Another approach is the incorporation of additives and fillers. The addition of thermal stabilizers, such as antioxidants and UV absorbers, can help slow down polymer degradation by preventing oxidation and structural breakdown. Reinforcing recycled PPS with glass fibers (GF) or carbon fibers (CF) strengthens the polymer matrix, improving both thermal and mechanical performance. Moreover, incorporating ceramic or metallic fillers, such as boron nitride (BN), alumina (Al_2O_3), or graphene-based materials, significantly boosts thermal conductivity by enhancing heat dissipation. Reactive extrusion and chain extenders are also effective in improving the thermal

properties of recycled PPS. During recycling, polymer chains undergo scission, leading to a decrease in molecular weight and performance. By introducing chain extenders, the broken polymer chains can be rebuilt, restoring strength and heat resistance. Additionally, compatibilizers can enhance the interaction between the polymer and fillers, leading to better thermal performance.

Blending recycled PPS with virgin PPS is another practical method for restoring lost properties. A controlled mixture of both materials helps compensate for reduced molecular weight, crystallinity, and thermal resistance, ensuring a balance between performance and cost-effectiveness. Finally, optimizing processing conditions can help minimize further degradation. Controlling temperature, shear stress, and oxygen exposure during reprocessing prevents excessive polymer breakdown, preserving the material's structural integrity and thermal stability (Costa et al. 2023).

APPLICATIONS FOR RECYCLED PPS IN AEROSPACE ENGINEERING

With increasing emphasis on sustainability and cost efficiency, the aerospace industry has begun exploring the use of recycled Polyphenylene Sulfide (PPS) in various applications. Due to its high thermal stability, chemical resistance, and excellent mechanical properties, PPS is widely used in aviation. Although virgin PPS remains the preferred choice for structural and load-bearing components, advancements in material recovery and processing have made recycled PPS a viable alternative for several non-structural and semi-structural aerospace applications (De Fazio et al. 2023).

Recycled PPS is extensively utilized in aircraft interiors as shown in Figure 6, where materials must be lightweight, flame-resistant, and durable while maintaining aesthetic and functional performance. One of its primary uses is in cabin panels and sidewalls, which require materials capable of withstanding temperature variations and impact forces while contributing to overall weight reduction for fuel efficiency. Additionally, it is used in overhead compartments and storage bins, offering durability and resistance to wearing over extended operational cycles. Other important applications within the aircraft interior include seat components, tray tables, and armrests, where strength and fatigue resistance are crucial. Furthermore, PPS is used in ventilation ducts and air distribution systems, as it provides excellent resistance to high temperatures, humidity, and chemicals, ensuring long-term reliability in cabin air circulation and temperature control (Montagna et al. 2022).

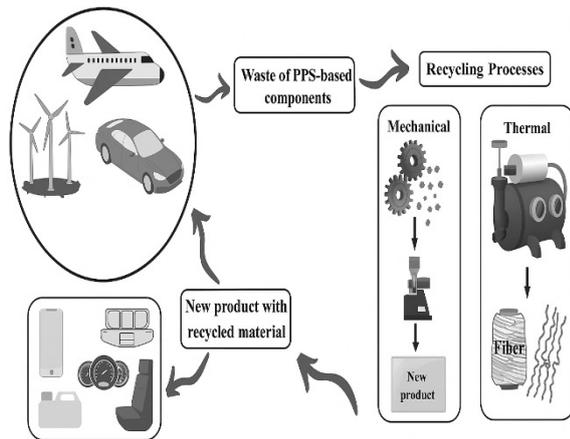


FIGURE 6. Applications of Recycled PPS (Chen et al. 2021)

Although load-bearing and primary structural elements in aircraft still depend on virgin PPS or other high-performance composites, recycled PPS is being explored for exterior accessories and secondary structures. It is commonly used for protective covers and enclosures, particularly in areas requiring UV, heat, and chemical resistance. These protective elements help shield sensitive components from environmental exposure, prolonging their lifespan. In addition, recycled PPS is used in brackets, clamps, and fasteners, where moderate mechanical strength and weight reduction are key considerations. Non-structural fairings and aerodynamic covers are also potential applications, as PPS can be molded into complex shapes while retaining heat and chemical resistance. These components benefit from recycled PPS's ability to withstand high-altitude conditions, temperature fluctuations, and prolonged UV exposure (Deng et al. 2015).

The electrical and mechanical systems in aircraft also benefit from the use of recycled PPS due to its superior dielectric properties, thermal resistance, and chemical inertness. One major application is in wire insulation and cable coatings, where PPS protects electrical systems from extreme temperatures, moisture, and corrosive chemicals commonly found in aviation environments (Momanyi et al. 2019).

By leveraging additive manufacturing, interior parts mentioned can be designed with intricate geometries that reduce weight while maintaining structural integrity. The ability to print on-demand replacement parts also enhances maintenance efficiency and cost savings in the aerospace industry. In aviation, metallic brackets and mounting fixtures contribute significantly to aircraft weight. Replacing these components with recycled PPS composites reinforced with carbon or glass fibers offers a lighter yet structurally sound alternative. Using AM, aerospace

engineers can fabricate avionics mounting structures, equipment enclosures, and cable management systems that offer heat resistance, dielectric properties, and fire retardancy (Momanyi et al. 2019).

Unmanned Aerial Vehicles (UAVs) as shown in Figure 7 and satellite components require lightweight and durable materials to maximize payload efficiency. Recycled PPS, when used in additive manufacturing, enables the production of aerodynamic fairings, sensor enclosures, and structural reinforcement elements that can withstand harsh environmental conditions. Given its chemical resistance and high thermal stability, recycled PPS is ideal for protective casings and thermal shielding in aerospace applications. Additionally, PPS-based components can be tailored to specific mission requirements, providing a cost-effective alternative for UAV and satellite manufacturers (Charitidis J. Panagiotis, 2024).

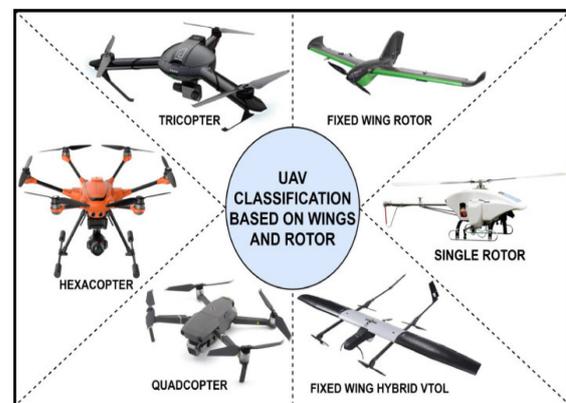


FIGURE 7. Types of Unmanned Aerial Vehicles (UAVs) (Mark Detergous, 2025)

Recycled PPS is well-suited for heat-resistant applications, particularly in engine compartments, exhaust systems, and thermal management solutions. Using additive manufacturing, manufacturers can produce custom-designed ducts, manifolds, and cooling system components with improved heat dissipation and durability. Other potential applications include protective engine covers and high-temperature-resistant insulators, which safeguard critical aerospace components from extreme thermal and mechanical stress. The ability to print these parts on demand further enhances the efficiency of repair and maintenance operations in the aerospace sector (T. Li et al. 2024).

Until now, recycled PPS has emerged to be a sustainable material that suits aerospace industries applications while persisting to achieve sustainable development goals (SDGs) as shown in Figure 8. There are some successful case studies to be discussed, which similar approach can be implemented, especially targeted

towards Goal 9 and Goal 11. Firstly, Toray Industries developed a proprietary compounding process to recycle glass fibre-reinforced PPS (GFRP-PPS), achieving mechanical strength comparable to virgin materials. This technology blends PPS resin with special reinforcing fibres, maintaining performance even when recycled material constitutes 50% or more of the GFRP-PPS. The process also contributes to sustainability by reducing CO₂ emissions by at least 40%. Toray is collaborating with moulding companies to implement closed-loop recycling initiatives, supplying recycled GFRP-PPS pellets back to customers, thereby promoting a circular economy within the aerospace sector (De Bruijn et al. 2017).



FIGURE 8. Sustainable Development Goals (United Nations 2015)

Secondly, PEAK Performance Compounding assisted an extrusion processor in reducing waste by implementing a closed-loop recycling system for PPS profile extrusion. The processor faced high levels of PPS scrap, which PEAK converted into reusable pellets. These recycled pellets were blended with virgin resin for non-critical products, effectively minimizing waste and supporting sustainability efforts. This case demonstrates the practical application of recycled PPS in maintaining material efficiency within aerospace manufacturing processes (De Bruijn et al. 2017).

Thirdly, GKN Fokker achieved a significant milestone by conducting the first successful flight of an aircraft equipped with components made from recycled thermoplastic composites. The project, led by the ThermoPlastic Composite Application Centre (TPAC) under the TPC Cycle initiative, focused on creating an access panel for an experimental rotorcraft. This panel was manufactured using reclaimed Toray Cetex® TC1100 carbon/PPS continuous fiber-reinforced thermoplastic composites. The recycling process involved converting the reclaimed materials into an extruded form, which was then

compression molded into the final component, achieving high mechanical properties suitable for aerospace applications (Chen et al. 2021).

CHALLENGES OF RECYCLING PPS IN AEROSPACE INDUSTRY

It is important to consider the challenges of recycled PPS to be implemented in the aerospace industry. Firstly, the use of recycled Polyphenylene Sulfide (PPS) in aerospace components must comply with strict certification standards set by the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA). These regulatory bodies ensure that all materials used in aircraft manufacturing meet stringent safety, performance, and durability requirements before approval. Both FAA and EASA, as demonstrated in Figure 9, require that materials, including recycled PPS, undergo thorough qualification processes to verify their reliability under different operating conditions. The material must consistently meet predefined mechanical and physical properties to ensure its suitability for aerospace applications. Manufacturing processes must also adhere to strict quality control measures to maintain consistency and repeatability. Both FAA and EASA recognize standards such as FAA Advisory Circular (AC) 20-107B and EASA's Certification Specifications (e.g., CS-25) for verifying the performance of composite materials. For interior components, one of the most crucial aspects is compliance with flammability and fire safety standards. According to FAA FAR 25.853 and its European equivalent CS 25.853, materials must pass vertical and horizontal burn tests, demonstrate low smoke density (ASTM E662), and show minimal toxic gas emissions (e.g., BSS 7239 or Airbus ABD0031). The FAA's Order 8110.4C outlines detailed process specifications, ensuring that materials and components produced through recycling maintain the same level of quality as their virgin counterparts (Montagna et al. 2022).



FIGURE 9. Regulatory Bodies of Aerospace Manufacturing (Jason Kuligmate 2023)

Besides, aerospace applications demand extremely high-purity materials to guarantee reliability and safety. Recycled PPS often contains impurities due to contamination during the collection and processing stages. Foreign particles, residual additives, and degradation by products can compromise the material’s properties, making it difficult to meet the strict quality standards required for aircraft components. Advanced filtration, purification, and sorting techniques are necessary to achieve the required purity levels, but these processes add complexity and cost to recycling (H. Li et al. 2014).

Next, maintaining consistent mechanical and thermal properties in recycled PPS is another significant challenge. Recycled materials can exhibit variations in tensile strength, impact resistance, and heat deflection temperature due to differences in processing conditions, prior usage, and degradation during re-melting. In aerospace applications, where precision and reliability are crucial, these inconsistencies can limit the usability of recycled PPS. Manufacturers must implement strict quality control measures and standardized processing techniques to minimize variations and ensure that recycled PPS meets performance expectations(Chen et al. 2021).

While recycling PPS can contribute to sustainability efforts, the cost of processing, purification, and requalification can be high. The additional expenses associated with maintaining purity, enhancing material properties, and meeting certification standards may offset the cost savings of using recycled material. The economic feasibility of recycled PPS depends on advances in recycling technology, process optimization, and increasing demand for sustainable aerospace materials. Figure 10 shows an instance of the relevant cost to recycle plastics(Jiun et al. 2016).

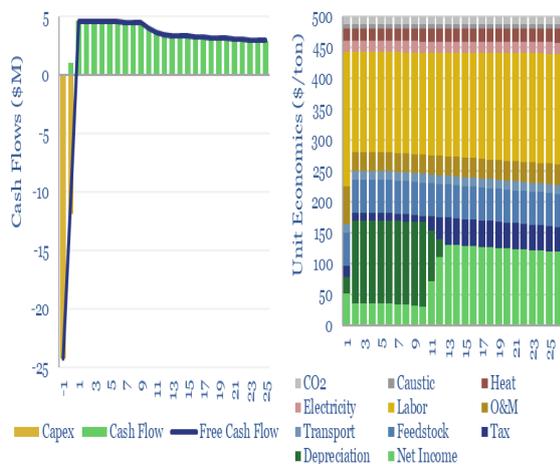


FIGURE 10. Cost of Recycle Plastics (Jennie Soluty 2022)

In aerospace applications, PPS is frequently used as a matrix material in fiber-reinforced composites, such as PPS/carbon fiber (PPS/CF) or PPS/glass fiber (PPS/GF) laminates. While these composites offer excellent mechanical properties, their structure makes material separation challenging. The strong bonding between PPS and reinforcing fibers prevents easy mechanical or chemical separation. Traditional mechanical recycling methods, such as grinding and re-melting, often result in fiber degradation and a loss of structural integrity. Advanced separation techniques, such as thermal depolymerization or selective dissolution, are required to effectively recover PPS without compromising its quality (Kadhim et al. 2023).

Many aerospace components utilize multilayer materials, where PPS is combined with adhesives, coatings, or other polymers to enhance performance. These layers are often difficult to separate, as they are designed to be highly durable and resistant to thermal or chemical breakdown. As a result, recycled PPS extracted from multilayer components may contain residual impurities from other materials, affecting its purity and mechanical properties. Specialized recycling methods, such as chemical processing or supercritical fluid treatment, may be required to selectively extract PPS while minimizing contamination. In addition, the high-performance requirements of aerospace-grade PPS often mean it undergoes extensive processing, including exposure to high temperatures, oxidation, and mechanical stress. Over time, repeated processing can lead to polymer chain scission, reduced crystallinity, and diminished mechanical strength. This degradation is exacerbated when PPS is recovered from complex structures, as the separation process itself can further damage the material. To counteract these effects, manufacturers may need to incorporate stabilizers, compatibilizers, or reinforcement additives to restore the properties of recycled PPS(Luo et al. 2016).

Recycling PPS requires sophisticated processing methods to maintain its high-performance properties. Techniques such as thermal depolymerization, chemical recycling, and supercritical fluid processing are expensive due to the energy-intensive nature of these methods. Additionally, separating PPS from fiber-reinforced composites, multilayer materials, and mixed polymer streams adds complexity and cost to the recycling process. Another factor affecting economic viability is the cost of quality control and certification. Recycled PPS must meet stringent industry standards, requiring extensive testing, material validation, and process monitoring. These additional steps can offset the financial benefits of using recycled material, making virgin PPS a more attractive option in some cases(T. Li et al. 2024).

For recycled PPS to become a viable alternative to virgin material, recycling technologies must be scalable to meet industrial demand. However, the infrastructure for large-scale PPS recycling is still developing, and most current methods operate on a limited scale. The aerospace industry produces a relatively small volume of recyclable PPS compared to other thermoplastics, making it challenging to achieve economies of scale. Innovations in recycling processes, such as automated material sorting, improved depolymerization techniques, and the use of compatibilizers to enhance recycled PPS properties, are crucial for increasing scalability. Establishing standardized recycling practices and integrating them into existing supply chains can also improve efficiency and cost-effectiveness (Montagna et al. 2022).

CONCLUSION

The review highlights critical advancements and challenges in the recycling of Polyphenylene Sulfide (PPS) for aerospace applications. While mechanical and chemical recycling methods have made strides in material recovery, maintaining the mechanical and thermal integrity of recycled PPS remains a challenge. Mechanical recycling, though cost-effective, leads to polymer degradation, reducing tensile strength, impact resistance, and crystallinity. On the other hand, chemical recycling can restore polymer purity but is hindered by high energy consumption and the use of hazardous chemicals. The current state of PPS recycling demonstrates both progress and limitations. While recycled PPS is increasingly viable for non-structural aerospace applications such as aircraft interiors and ventilation systems, its use in load-bearing components remains restricted due to reduced mechanical performance. The lack of standardized testing and certification further hampers its widespread adoption. Additionally, contamination, polymer degradation, and processing costs pose barriers to large-scale implementation. Recycling PPS directly supports sustainability goals by reducing polymer waste, lowering carbon emissions, and contributing to circular economy initiatives. By diverting PPS waste from landfills and incineration, recycling promotes resource efficiency and environmental responsibility within aerospace manufacturing. The ability to recover and reuse PPS, particularly with reinforcement strategies, aligns with the industry's push toward greener materials and reduced reliance on virgin polymers. This review also identifies significant gaps in PPS recycling, including the absence of standardized recycling protocols, insufficient scalability of existing processes, and the need for improved reinforcement techniques to enhance

mechanical properties. Furthermore, challenges related to contamination, processing complexity, and economic feasibility require further research to optimize recycling methodologies.

Additionally, considering the intrinsic properties of PPS- namely its mechanical strength, thermal resistance, and chemical stability-emerging applications in other sectors are promising. These include sustainable automotive components like under-the-hood parts and battery casings, renewable energy systems such as solar panel frames and wind turbine components, electronics and semiconductor industry parts like insulation and circuit board housings, and consumer goods and sports equipment, including kitchen appliances and protective gear.

Besides, future research should explore novel reinforcement approaches such as hybrid fiber reinforcements, compatibilizers, and advanced additive manufacturing techniques to improve the structural integrity of recycled PPS. Additionally, efforts to develop low-energy chemical recycling methods and closed-loop recycling systems could enhance the sustainability and cost-effectiveness of PPS recovery. Addressing regulatory and certification challenges is also crucial to ensuring the viability of recycled PPS in aerospace applications. The significance of this review lies in its comprehensive evaluation of PPS recycling methods, their mechanical, physical and thermal properties, their limitations, and their potential for sustainable aerospace manufacturing. By addressing key barriers and identifying opportunities for further exploration, this study provides a roadmap for advancing PPS recycling technologies and expanding their applications within high-performance engineering sectors.

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DECLARATION OF COMPETING INTEREST

None.

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