

## Review

# Leakage Mechanisms and Airtightness Challenges in FFF-Printed Soft Pneumatic Actuators: A Scoping Review

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## Abstract

Fused filament fabrication (FFF) is one of the most widely adopted additive manufacturing methods for thermoplastic polyurethane (TPU)-based soft pneumatic actuators, enabling low-cost fabrication, geometric customization, embedded pneumatic architectures, and rapid prototyping for soft robotic systems. However, despite these advantages, achieving reliable airtightness remains a major challenge due to process-induced anisotropy, inter-layer voids, incomplete filament fusion, residual porosity, seam discontinuities, material permeability, and interface-related leakage. These defects can significantly reduce pressure retention, actuation efficiency, deformation repeatability, and long-term pneumatic reliability. This review systematically examines the dominant leakage mechanisms affecting FFF-printed soft pneumatic actuators and comparatively analyzes fabrication approaches, TPU material systems, geometric design factors, post-processing methods, sealing strategies, and leakage characterization techniques. Representative experimental observations, including pressure-decay testing, submerged-bubble visualization, microscopy, and localized thermal surface treatment, are also discussed to connect the findings reported in the literature with experimentally observed leakage behavior. Emerging analytical leakage models, sensing technologies, AI-assisted predictive monitoring, and digital-twin-enabled manufacturing frameworks are reviewed as promising approaches for developing leakage-aware soft robotic systems. The review highlights current limitations related to standardized leakage testing, cyclic durability evaluation, scalable sealing strategies, and intelligent manufacturing integration. Overall, airtightness is identified as a coupled material-process-geometry challenge that must be systematically addressed to improve the reliability, scalability, and long-term operational stability of next-generation TPU-based soft pneumatic actuators. The review was conducted following the PRISMA-ScR framework and includes 248 studies published between 2017 and 2026.

**Keywords:** soft robotics; TPU; fused filament fabrication; airtightness; pneumatic actuators; additive manufacturing; air leakage; interlayer bonding; post-processing; digital twin



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## 1. Introduction

Soft robotic systems have emerged as a transformative research field because their compliant structures enable safe interaction, adaptive deformation, and operation in complex and unstructured environments [1,2]. Unlike conventional rigid robots, soft robots can achieve biologically [3,4] and origami-inspired [5] motion while maintaining mechanical

flexibility, environmental adaptability, and safer interaction with humans and delicate objects. These characteristics have enabled a wide range of applications in biomedical devices [6], wearable assistance systems [7,8], rehabilitation technologies [9–12], industrial gripping systems [13,14], adaptive manipulation [15–17], exploration platforms [18], and human-robot interaction [19,20]. The growing demand for lightweight, compliant, and multifunctional robotic systems has consequently accelerated research into flexible materials, intelligent actuation architectures, and advanced manufacturing strategies for next-generation soft robotic platforms.

Soft robotic systems employ various actuation mechanisms to achieve compliant motion, adaptive deformation, and multifunctional behavior. Common actuation approaches include pneumatic and hydraulic actuation [21–25], tendon-driven systems [26–28], dielectric elastomer actuation [29–31], shape-memory alloys [32,33], electroactive polymers [34,35], magnetic actuation [36–38]. Among these approaches, pneumatic actuation remains one of the most widely adopted methods because they provide lightweight operation, high power-to-weight ratio, large deformation capability, relatively simple system integration, and inherent operational safety during human-robot interaction. The integration of additive manufacturing and flexible material systems has further expanded the capabilities of pneumatic soft robotic systems by enabling customizable actuator geometries, embedded sensing, multifunctional deformation modes, and low-cost fabrication for biomedical, industrial, wearable, and exploratory applications.

Recent advances in soft robotics have significantly expanded the range of actuator architectures and application domains. Pneumatic networks (PneuNet) actuators have demonstrated improved contact area, grasping adaptability, and bending capability in soft robotics, with bending angles approaching  $180^\circ$  under relatively low operating pressure [39]. Pneumatic soft robotic systems have also been explored for wearable healthcare and compression therapy applications because their compliant structures enable safer and more adaptive human interaction [40]. In locomotion applications, ocean-wave-inspired crawling soft robots have demonstrated improved terrain adaptability and load-bearing capability through integrated additive manufacturing and pneumatic control architectures [41]. Prestressed thin-plate pneumatic actuators have further demonstrated compact, lightweight, and high-frequency actuation capability in grippers, hinges, and jellyfish-inspired robotic systems [42–44]. Hybrid pneudraulic actuation has also been proposed to improve response speed, motion precision, and acoustic performance in soft fluidic robotic systems for biomedical and industrial applications [45].

Conventional soft pneumatic actuators are typically fabricated using silicone molding because cross-linked elastomeric structures provide excellent compliance and relatively reliable airtightness [46,47]. Molded silicone structures can produce continuous, defect-free pneumatic chambers; however, the fabrication process often requires multi-step molding, curing, tooling, and manual assembly [48,49]. These limitations reduce manufacturing scalability, restrict rapid design iteration, and complicate the fabrication of embedded internal channels and complex geometries. Additive manufacturing (AM) enables digitally controlled fabrication of pneumatic chambers, embedded flow paths, integrated connectors, and customized actuator architectures [50].

Among the available additive manufacturing methods, fused filament fabrication (FFF), also known as fused deposition modeling (FDM), is one of the most widely adopted fabrication approaches for soft pneumatic actuators because of its compatibility with thermoplastic polyurethane (TPU) and other filament materials [51]. Recent developments in pellet-based extrusion and fused granulate fabrication have further expanded manufacturing flexibility by enabling the processing of highly compliant thermoplastic elastomers and the fabrication of large-scale airtight pneumatic structures [50].

Recent advances in hybrid manufacturing (HM) have also demonstrated the potential of integrating additive and subtractive processes within a single manufacturing platform to improve geometric complexity, surface integrity, dimensional accuracy, and process efficiency [52]. These developments provide a pathway to reduce interlayer defects, improve sealing quality, and enhance airtightness reliability beyond conventional standalone FFF fabrication. Emerging intelligent manufacturing frameworks integrating sensing technologies, AI-assisted monitoring, adaptive process control, and digital-twin-enabled manufacturing have further demonstrated the potential for improving manufacturing reliability, defect prediction, and soft robotic system performance [53].

Despite these advances, airtightness remains one of the most significant unresolved challenges in FFF-printed soft pneumatic actuators [54]. Airtightness directly governs pressure retention, deformation repeatability, actuation efficiency, controllability, and long-term operational durability. Leakage in FFF-printed TPU structures commonly originates from incomplete interlayer bonding, non-uniform filament deposition, residual micro-porosity, seam discontinuities, and weak connector interfaces [53]. Although these defects are often not visible, they can form interconnected microchannels that become active leakage pathways under internal pressure. Although high infill settings are commonly adopted to improve sealing performance, fully dense and airtight structures are not always achieved because interlayer discontinuities, imperfect bead packing, and the inherent permeability of TPU may persist even when slicer settings specify 100% infill [55]. Recent studies have also explored surface sealing, localized thermal treatment, pressure-decay analysis, and machine-learning-assisted leakage prediction frameworks [56,57] to improve pneumatic reliability and enable leakage-aware manufacturing of TPU-based soft robotic systems [58].

Although this review primarily focuses on filament-based fused filament fabrication (FFF) of airtight soft pneumatic actuators, selected studies on fused granulate fabrication (FGF), silicone molding, rapid liquid printing (RLP), vat photopolymerization, and hybrid manufacturing are included for comparative purposes to highlight their respective advantages, limitations, and implications for improving FFF-based actuator fabrication. This review systematically examines leakage mechanisms, material-related limitations, airtightness enhancement strategies, and leakage-aware predictive frameworks for FFF-printed soft pneumatic actuators. The main contributions of this review are summarized as follows:

- Comprehensive review of leakage mechanisms in FFF-printed TPU actuators.
- Classification of major leakage sources and defect pathways.
- Comparative analysis of fabrication, sealing, and airtightness enhancement strategies.
- Identification of current challenges and future research directions for leakage-aware soft robotic systems.

## 2. Methodology

### 2.1. Review Scope and Literature Collection

A structured scoping review based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) framework was conducted to systematically investigate airtightness limitations, leakage mechanisms, material-related challenges, fabrication strategies, and mitigation approaches associated with FFF-printed soft pneumatic actuators. Relevant studies published between 2017 and 2026 were retrieved from major scientific databases, including Scopus, Web of Science, Wiley, Taylor & Francis, Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, and MDPI. The literature search employed combinations of keywords related to soft robotics, pneumatic actuators, thermoplastic polyurethane (TPU), fused filament fabrication (FFF), fused deposition

modeling (FDM), airtightness, leakage, permeability, interlayer bonding, porosity, sealing, post-processing, predictive monitoring, and AI-assisted additive manufacturing.

Comparative fabrication approaches, including fused granulate fabrication (FGF), silicone molding, rapid liquid printing (RLP), vat photopolymerization, and hybrid manufacturing, were included only when they provided relevant benchmarks for evaluating the fabrication, airtightness, or performance of filament-based FFF soft pneumatic actuators. Unless otherwise stated, the discussion and conclusions presented in this review refer specifically to filament-based FFF.

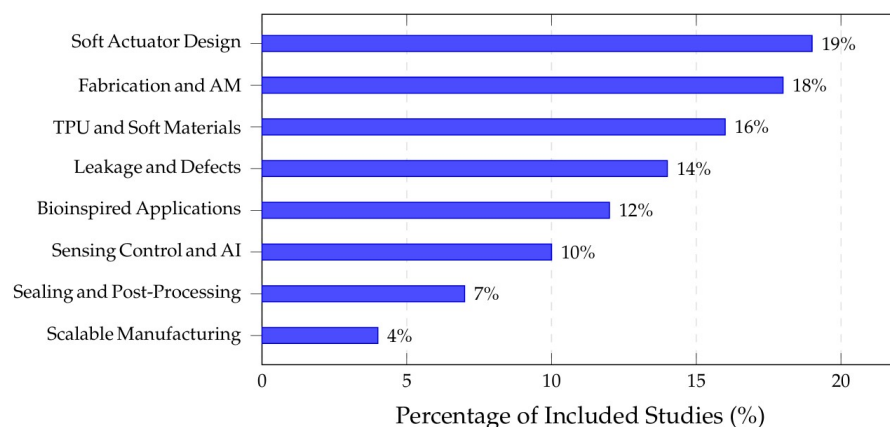
## 2.2. Review Protocol and Eligibility Criteria

This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines. The review protocol was retrospectively registered with the Open Science Framework (OSF) (Registration DOI/URL: <https://osf.io/ers6v/metadata/osf> (accessed on 15 June 2026)). It was registered after completion of the initial manuscript and before peer review to improve transparency and reproducibility.

Studies were considered eligible if they addressed soft robotic actuators, soft pneumatic actuators, fused filament fabrication (FFF), fused deposition modeling (FDM), thermoplastic polyurethane (TPU), airtightness, leakage characterization, pressure-retention behavior, additive manufacturing strategies, sensing technologies, modeling approaches, or actuator performance evaluation. Publications focusing exclusively on rigid robotic systems, unrelated manufacturing technologies, patents, non-technical reports, or studies lacking sufficient technical detail were excluded. Following the application of the eligibility criteria, studies published between 2017 and 2026 were included in the final review corpus.

## 2.3. Technical Classification and Comparative Analysis

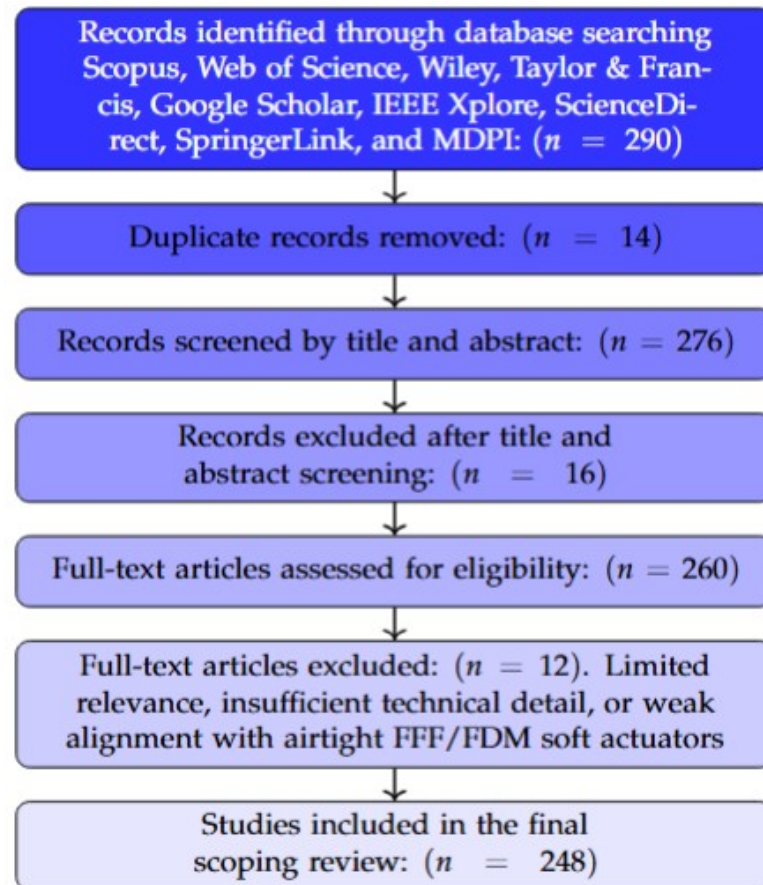
The 248 studies included in this scoping review were classified into eight primary technical categories based on their primary research objective and dominant technical contribution: (i) soft actuator design, (ii) fabrication and additive manufacturing, (iii) TPU and soft materials, (iv) bioinspired and origami systems, (v) leakage and defects, (vi) sensing, control, and artificial intelligence, (vii) sealing and post-processing, and (viii) scalable manufacturing. Figure 1 illustrates the distribution of the reviewed studies across these technical categories. To avoid double-counting, each publication was assigned to a single primary category according to its dominant technical contribution. For studies addressing multiple research themes, classification was based on the main objective emphasized by the authors and the primary contribution reported in the study. Accordingly, the reported percentages represent the proportion of the total 248 reviewed studies assigned to each technical category.



**Figure 1.** Representative distribution of reviewed studies by technical focus area.

#### 2.4. Study Selection and Data Synthesis

The study selection process followed the PRISMA-ScR framework and is summarized in Figure 2. Retrieved records were screened by title, abstract, and full-text review to ensure relevance to airtight soft robotic actuators, fabrication methodologies, material systems, leakage mechanisms, sensing technologies, post-processing approaches, and actuator performance. Duplicate records were removed prior to screening.



**Figure 2.** PRISMA-ScR flow diagram.

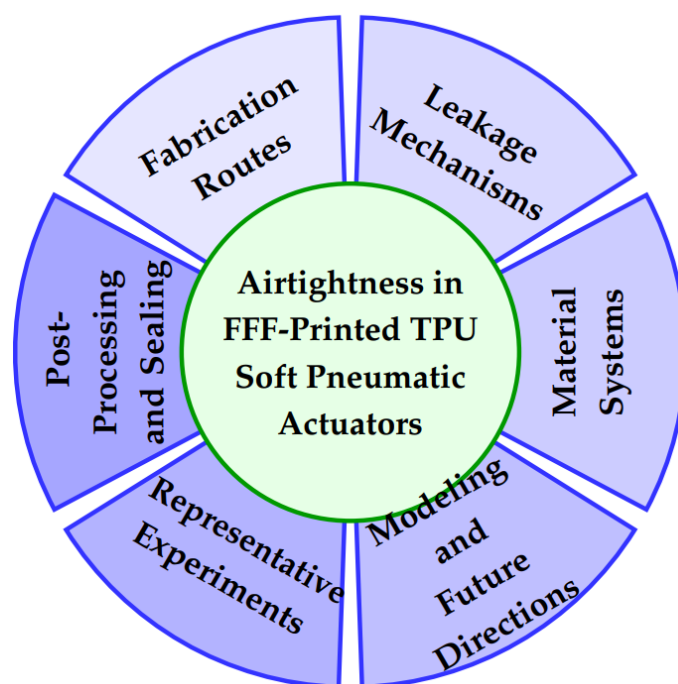
For each eligible study, information on actuator architecture, fabrication process, material selection, airtightness enhancement techniques, sensing methodologies, pressure-retention performance, modeling approaches, and reported limitations was extracted and systematically synthesized. The reviewed literature was subsequently organized into thematic categories to identify research trends, technological developments, knowledge gaps, and future research opportunities related to airtight FFF-printed soft pneumatic actuators.

#### 2.5. Critical Appraisal of Individual Studies

A formal critical appraisal of individual studies was not performed. The primary objective of this scoping review was to systematically map, categorize, and synthesize the available literature related to airtight FFF-printed soft pneumatic actuators rather than to evaluate the methodological quality or risk of bias of individual studies. Consistent with PRISMA-ScR recommendations, the review focused on identifying research trends, technological developments, fabrication strategies, leakage mechanisms, material systems, and future research opportunities across the field.

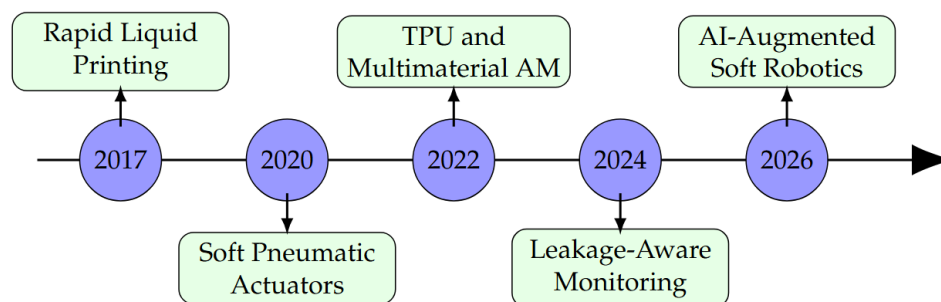
## 2.6. Review Organization

The organizational framework of this review is illustrated in Figure 3. The framework integrates fabrication routes, leakage mechanisms, material systems, sealing strategies, representative experiments, and predictive modeling into a unified leakage-aware soft robotics framework. The remainder of this paper is organized as follows. Section 3 reviews fabrication approaches for soft robotic actuators, Section 4 discusses leakage mechanisms in FFF-printed TPU actuators, Section 5 compares material systems, Section 6 examines additive manufacturing and fabrication strategies, Section 7 summarizes post-processing techniques and airtightness enhancement methods, and Section 8 presents representative experimental observations, AI-assisted predictive frameworks, open challenges, and future research directions.



**Figure 3.** Review framework for airtight FFF-printed soft pneumatic actuators.

The historical progression of research themes related to airtight pneumatic soft robotic systems is summarized in Figure 4. The timeline presents a literature-based synthesis of representative milestones reported in the reviewed studies, illustrating the chronological evolution of research from early fabrication-focused studies to leakage-aware manufacturing, predictive monitoring, embedded sensing, and AI-assisted soft robotic systems.



**Figure 4.** Literature-based synthesis illustrating the evolution of soft pneumatic actuator fabrication and monitoring technologies from representative milestones reported in the reviewed studies.

Rapid liquid printing (RLP) for soft robotic fabrication was introduced by Hajaiah et al. [59], while comprehensive developments in soft pneumatic actuators were summarized by Walker et al. [46]. TPU-based additive manufacturing and multifunctional soft robotic fabrication strategies were further expanded through recent studies on soft robotic materials and 3D printing technologies [60]. More recent investigations have emphasized leakage-aware monitoring, defect prediction, and AI-assisted additive manufacturing frameworks for intelligent soft robotic systems [61,62].

### 3. Soft Robotic Actuator Fabrication

To improve readability and minimize overlap among related topics, this review is organized into distinct sections covering actuator design, material systems, additive manufacturing strategies, leakage mechanisms, post-processing techniques, and representative experimental observations. This section focuses on actuator fabrication routes and structural design concepts rather than material selection or manufacturing process optimization, which are discussed in Sections 5 and 6.

#### 3.1. Silicone Molding and Rapid Liquid Printing (RLP)

Soft pneumatic actuators have traditionally relied on silicone-based molding because cross-linked elastomeric materials provide high compliance, fatigue resistance, flexibility, and intrinsic airtightness [63,64]. Silicone materials used in soft robotic actuator fabrication commonly include polydimethylsiloxane (PDMS) [65,66], Ecoflex [67], Dragon Skin [68,69], Smooth-Sil [70,71], and other platinum-cured elastomers because of their high flexibility, biocompatibility, fatigue resistance [72–74], and favorable pneumatic sealing characteristics.

In molded soft actuators, the cured polymer network forms a continuous structure without layer interfaces, thereby minimizing the formation of through-wall leakage pathways. However, these processes generally require multiple fabrication stages, including mold design, casting, curing, demolding, bonding, and manual assembly [75,76]. These sequential procedures increase fabrication time, tool dependency, and geometric constraints while reducing manufacturing scalability and rapid design iteration.

Rapid Liquid Printing (RLP) [77] is an alternative fabrication technique in which uncured silicone is deposited within a supporting gel medium. Compared with conventional casting methods, RLP enables the fabrication of complex three-dimensional structures with reduced tooling requirements and enhanced geometric freedom. This approach preserves the favorable mechanical characteristics of silicone elastomers while improving manufacturing flexibility, scalability, and fabrication speed [59,78]. Comparative studies have demonstrated that RLP-fabricated pneumatic actuators can achieve elongation and deformation characteristics comparable to those of molded and polyjet-printed structures while exhibiting improved repeatability and fatigue longevity [51]. In addition, RLP enables the fabrication of multi-chamber pneumatic architectures and geometrically complex internal flow networks that are difficult to realize using conventional molding approaches [79]. These capabilities highlight the growing potential of silicone-based additive manufacturing for scalable fabrication of soft robotic actuators.

Despite these advantages, silicone molding and RLP-based approaches still face several limitations, including fabrication throughput, support-material handling, dimensional accuracy, and integration with embedded multifunctional features. Furthermore, although silicone structures generally exhibit superior airtightness compared with extrusion-based thermoplastic systems, the complexity of fabrication and limited compatibility with low-cost desktop manufacturing environments continue to motivate the exploration of alternative additive manufacturing approaches for soft pneumatic actuators.

### 3.2. Fused Filament Fabrication of TPU Actuators

Fused filament fabrication (FFF) is one of the most widely adopted additive manufacturing methods (AM) for TPU-based soft pneumatic actuators because of its low cost, accessibility, rapid prototyping capability, and compatibility with flexible thermoplastic materials [60,80]. Unlike conventional molding approaches, FFF enables direct layer-by-layer deposition of TPU into complex chambered geometries, embedded pneumatic channels [81], lattice structures [82,83], and monolithic actuator architectures [84–86] without requiring molds or extensive post-assembly processes. This capability makes FFF highly attractive for customized soft robotic systems, rapid design iteration, laboratory-scale prototyping, wearable robotics, and bioinspired actuator fabrication.

Recent developments in TPU-based AM have significantly expanded the functionality and application range of FFF-printed soft robotic systems. Fused granulate fabrication (FGF) approaches have demonstrated the capability to process highly compliant thermoplastic elastomers while enabling scalable fabrication of airtight pneumatic structures and multifunctional soft robotic devices [50]. Multi-material additive manufacturing has also enabled the integration of rigid and compliant structures within a single fabrication workflow, thereby improving actuator functionality and structural adaptability [87,88].

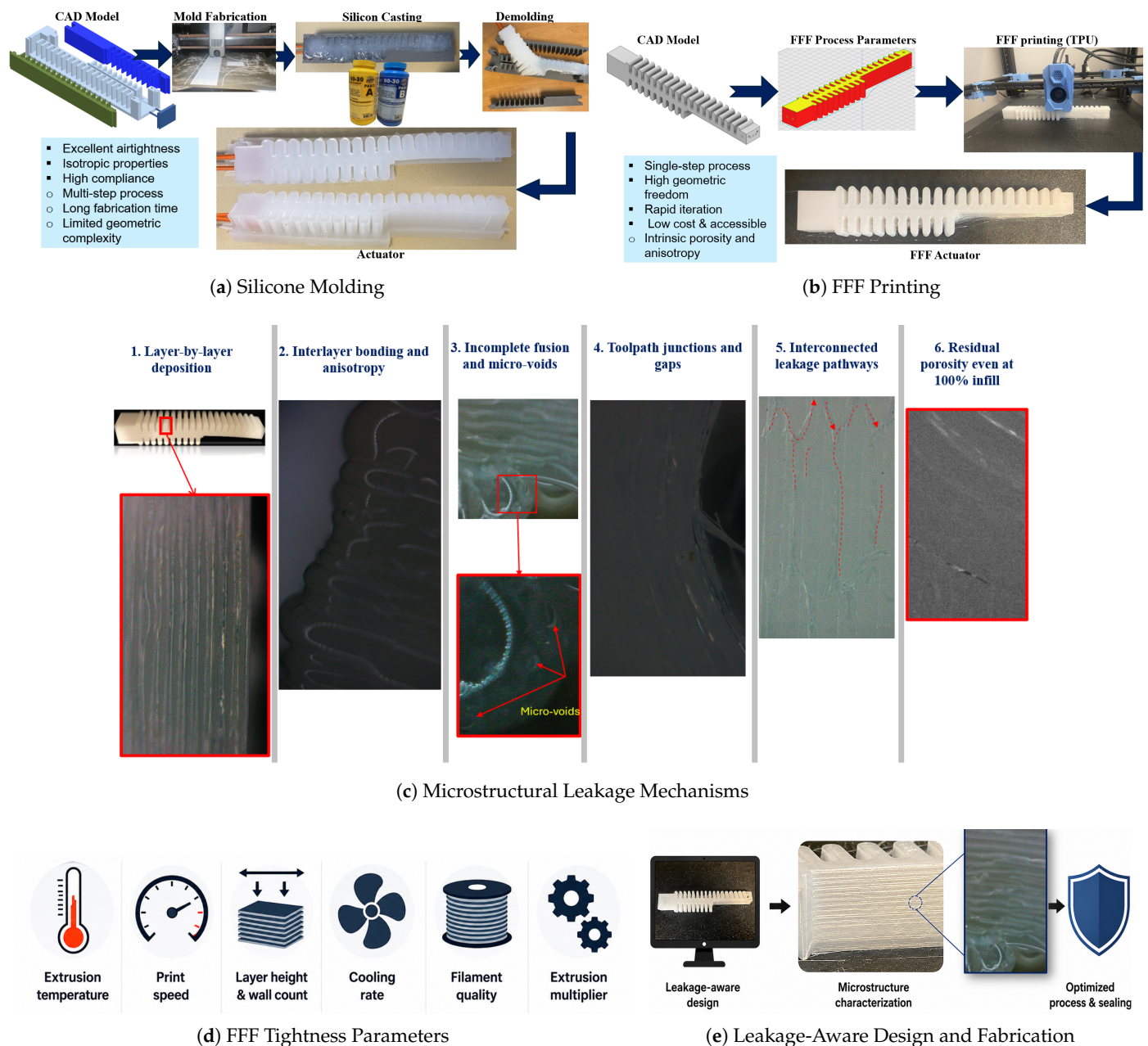
FFF remains fundamentally dependent on extrusion-based layer-by-layer material deposition, which introduces anisotropic mechanical behavior and process-dependent microstructural heterogeneity [89,90]. During fabrication, each deposited filament road is fused onto a partially cooled substrate, and the quality of interlayer bonding depends on nozzle temperature, extrusion consistency, flow rate, print speed, bead overlap, cooling conditions, and material rheology. Incomplete filament fusion can generate interfacial discontinuities, voids, seam defects, and residual porosity that subsequently function as leakage pathways under pneumatic loading conditions [91,92]. These process-induced defects significantly influence pressure retention capability, deformation repeatability, actuation efficiency, and long-term durability in pneumatic soft robotic systems [93].

The anisotropic nature of FFF further affects structural reliability because interlayer bonding strength is typically weaker than intralayer filament continuity [94]. As a result, leakage propagation often occurs preferentially along interfacial boundaries and seam regions, particularly under cyclic pressurization and repeated mechanical deformation. Additional factors, including nozzle path planning, infill density, raster orientation, and shell thickness, can also strongly influence airtightness performance by affecting bead packing quality and microstructural continuity within printed TPU walls.

Figure 5 illustrates the fundamental processes of silicone molding and FFF-based fabrication approaches for soft pneumatic actuators.

The transition from conventional molding to digitally controlled additive manufacturing, therefore, represents a major advancement in the fabrication of soft robotic actuators. However, the increasing adoption of TPU-based FFF systems has simultaneously elevated the importance of understanding process-induced defects, leakage mechanisms, and airtightness degradation in soft pneumatic actuators. Consequently, improving the reliability of airtightness in FFF-printed TPU systems remains a critical challenge for the development of scalable, durable, and high-performance soft robotic platforms.

Overall, the reviewed fabrication approaches demonstrate that actuator performance depends on the combined effects of fabrication strategy, material selection, and structural design. While silicone molding continues to provide superior intrinsic airtightness, FFF offers greater design flexibility and manufacturing accessibility, highlighting the need for improved leakage-aware fabrication strategies for TPU-based actuators.

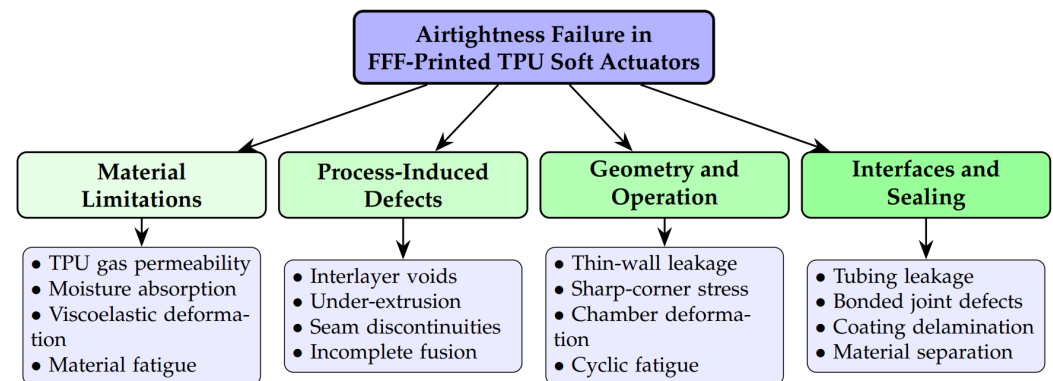


**Figure 5.** Overview of fabrication methods, leakage mechanisms, process parameters, and leakage-aware design strategies for FFF-printed soft pneumatic actuators: **(a)** Silicone molding provides excellent airtightness and isotropic behavior. **(b)** FFF printing enables rapid and geometrically complex fabrication but introduces anisotropy and leakage pathways. **(c)** Representative microstructural origins of leakage, including interlayer porosity, incomplete fusion, and seam defects. **(d)** Key FFF process parameters influencing airtightness and defect formation (Conceptual schematics). **(e)** Leakage-aware fabrication workflow integrating design, characterization, process optimization, and sealing strategies for improved pneumatic reliability.

#### 4. Leakage Mechanisms in FFF-Printed Soft Actuators

Airtightness degradation in FFF-printed soft pneumatic actuators results from coupled material, processing, geometric, and interfacial mechanisms. Leakage can arise from microscopic interfacial discontinuities, gas diffusion through the polymer matrix, process-induced porosity, cyclic deformation, stress concentrations, and connector-related sealing failures [95]. These mechanisms often interact simultaneously, making airtightness highly dependent on fabrication quality, material behavior, and long-term operating conditions.

Figure 6 summarizes the primary mechanisms contributing to leakage formation in FFF-printed soft actuators.



**Figure 6.** Primary mechanisms contributing to airtightness failure in FFF-printed soft pneumatic actuators.

#### 4.1. Material-Related Leakage Mechanisms

TPU-based soft pneumatic actuators exhibit several intrinsic material limitations that affect airtightness performance and long-term pressure retention. TPU exhibits inherent gas permeability because its polymeric microstructure permits gradual gas diffusion through the material matrix even in the absence of visible structural defects [96–98]. This diffusion-driven leakage mechanism becomes increasingly important in thin-wall actuators, high-pressure pneumatic systems, and long-duration pressurization conditions. Graphene-based nanofillers and composite reinforcement strategies have demonstrated the ability to reduce oxygen permeability by improving barrier properties and restricting gas transport pathways within the TPU matrix [99–102].

TPU materials are also sensitive to moisture absorption before printing. Trapped moisture may vaporize during extrusion and generate bubbles, porosity, and internal microvoids that subsequently function as leakage pathways under pneumatic loading [103,104]. TPU also undergoes time-dependent viscoelastic deformation during cyclic pressurization, allowing repeated deformation to gradually enlarge existing micro-defects and weaken interlayer bonding regions [105–107]. Repeated pneumatic loading can further introduce mechanical fatigue and localized stress softening in TPU structures, particularly near chamber walls and high-strain regions, thereby accelerating airtightness degradation and leakage propagation over time [108–110].

Collectively, these material-related mechanisms demonstrate that airtightness degradation in TPU soft actuators is governed not only by visible structural defects but also by intrinsic polymer behavior, environmental sensitivity, and long-term viscoelastic response.

#### 4.2. Process-Induced Defects and Print Anisotropy

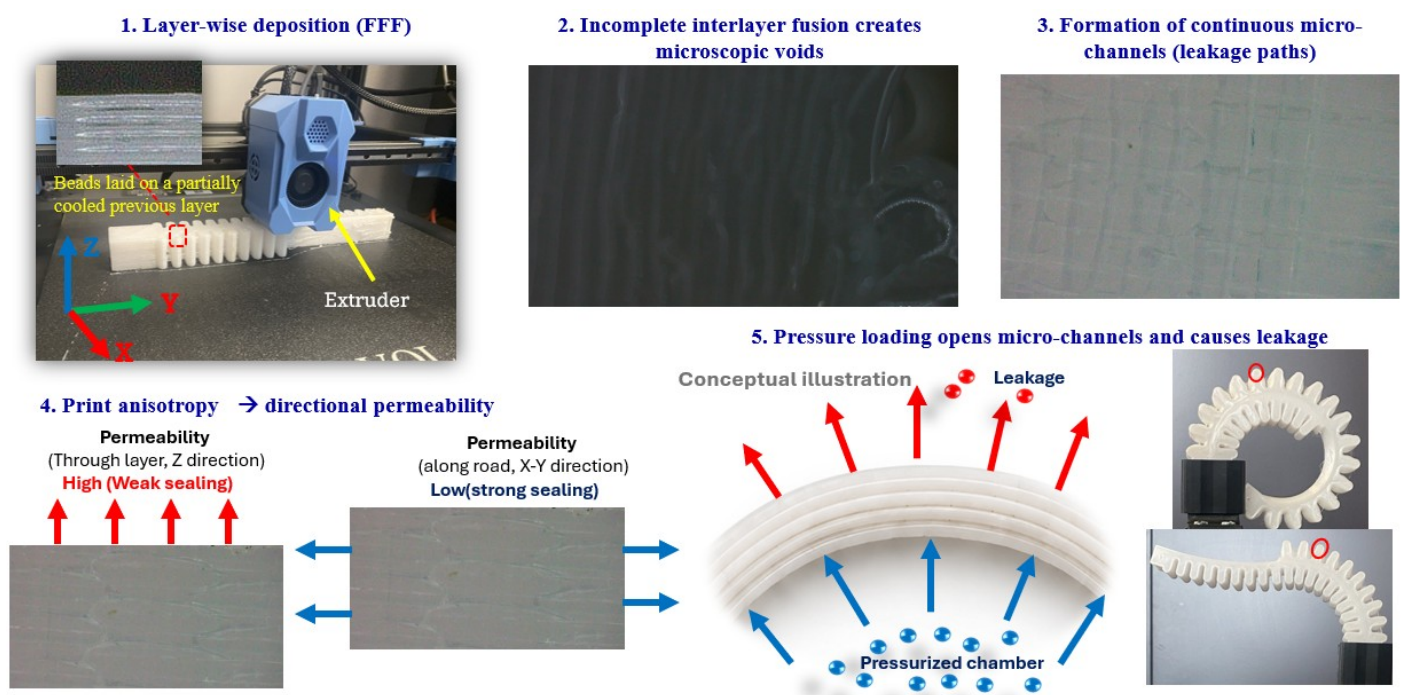
Process-induced defects are a dominant source of airtightness failure in FFF-printed soft pneumatic actuators. During the fabrication process, each deposited filament road cools before the subsequent layer is deposited [111]. If polymer-chain diffusion and melt fusion between adjacent layers are incomplete, microscopic interlayer voids remain within the printed structure [53]. These discontinuities can subsequently connect under internal pressurization and form active leakage micro-channels.

Under-extrusion further reduces filament overlap and produces insufficient wall density, thereby generating localized porous regions and weakly bonded interfaces that compromise airtightness [112,113]. Additional process-related defects, including seam discontinuities, nozzle start–stop irregularities, inconsistent flow rate, and unstable extru-

sion behavior, may also generate localized gaps and filament discontinuities that act as preferred leakage initiation sites [114,115]. Insufficient nozzle temperature or excessive print speed can reduce polymer diffusion between neighboring filament roads, thereby weakening interfacial bonding and increasing permeability [116–118]. Additional process instability may further generate localized wall-thickness variations and weak regions that subsequently leak under internal pressure [119–122].

FFF-fabricated TPU structures additionally exhibit strong anisotropic behavior because mechanical strength and sealing performance are generally higher along the filament deposition direction than across interlayer interfaces [123]. Tensile stresses normal to layer interfaces can progressively separate weakly bonded regions and promote leakage or delamination under repeated pneumatic loading. Directional permeability may therefore develop due to the preferential alignment of interlayer voids parallel to the build plane [124–126].

Figure 7 illustrates the formation of interlayer voids, print anisotropy, and pressure-induced leakage pathways in FFF-printed soft pneumatic actuators. AM soft materials remain susceptible to defects that can compromise geometric accuracy, mechanical reliability, and functional performance. Advanced monitoring techniques, including optical, thermal, tomographic, simulation-based, and AI-assisted approaches, have shown significant potential for defect detection, process optimization, and intelligent soft-material manufacturing [61].



**Figure 7.** Interlayer void formation, print anisotropy, and pressure-induced leakage in FFF-printed soft pneumatic actuators.

#### 4.3. Geometric and Operational Leakage Factors

Actuator geometry strongly influences leakage susceptibility and long-term pneumatic reliability [127,128]. Thin actuator walls improve flexibility and bending capability but reduce the number of sealing filament layers separating the internal chamber from the external environment [129–131]. Consequently, even small interfacial defects can become through-wall leakage pathways under internal pressurization. Sharp corners, abrupt thickness transitions, unsupported overhangs, enclosed chamber geometries, and discontinuous internal channels additionally increase stress concentration and reduce local print quality [132].

Repeated pneumatic loading may gradually enlarge existing micro-defects through viscoelastic creep and cyclic fatigue, thereby transforming initially inactive discontinuities into active leakage pathways [133]. Localized geometric discontinuities can further amplify strain concentration and promote progressive interfacial separation, particularly in highly compliant thin-wall actuator regions. Rounded transitions, continuous extrusion paths, sufficient wall thickness, and simplified internal chamber geometries can therefore improve pressure integrity while preserving actuator flexibility and functional deformation capability.

Several bioinspired actuator geometries have demonstrated improved controllability of deformation and structural efficiency through optimized pneumatic designs. Origami-inspired vacuum-driven soft actuators fabricated from thermoplastic polyurethane via fused filament fabrication demonstrated large bending deformation, a compact geometry, and enhanced adaptability for soft robotic gripping and locomotion applications [134]. The crease-free single-material architecture enabled high bending angles, improved structural flexibility, and efficient integration with vacuum-assisted grasping mechanisms while remaining compatible with consumer-level additive manufacturing systems [135]. Bio-inspired foldable pneumatic joint actuators demonstrated efficient rotational deformation under ultralow operating pressures through optimized folding membrane geometries and elastic chamber integration [136,137].

#### 4.4. Interface and Sealing Challenges

Macroscopic interfaces frequently dominate leakage behavior even when the printed actuator wall itself exhibits acceptable airtightness. Tubing connections, bonded fittings, press-fit pressure ports, and multi-material joints experience repeated mechanical loading, cyclic deformation, and localized stress concentration during actuator operation [138,139]. Poor sealing at these interfaces may therefore mask the actual airtightness capability of the printed TPU structure. As discussed in Section 8.3, the baseline airtightness of the pneumatic system is examined before evaluating leakage in the soft robot.

Protective sealing coatings and post-processing strategies have been investigated to improve pressure retention and reduce surface-connected porosity in FFF-printed TPU actuators. Silicone surface coatings improve airtightness by forming a compliant conformal barrier that penetrates superficial porosity while preserving actuator flexibility [140]. Epoxy sealing approaches can also reduce leakage by forming rigid, impermeable surface layers; however, excessive sealing may reduce actuator compliance and deformation capability [141]. Coating delamination, cracking, or material separation during cyclic deformation may subsequently generate new leakage pathways and reduce long-term sealing effectiveness [142,143]. As discussed in Section 7.2, localized hot-air treatment mitigates leakage by improving interfacial fusion and sealing surface-connected microvoids in TPU structures.

## 5. Material Systems for Airtight Soft Pneumatic Actuators

Unlike the previous section, which focuses on fabrication approaches, this section compares the intrinsic properties of material systems that influence airtightness and actuator performance.

### 5.1. Commercial TPU Filaments

Among the available elastomeric materials, TPU has emerged as the dominant choice for FFF-based soft pneumatic actuators because it provides a favorable balance between elasticity, flexibility, abrasion resistance, toughness, and printability [144–146]. TPU materials enable the fabrication of compliant chambered structures, embedded pneumatic channels, flexible membranes, and multifunctional soft robotic architectures. These characteristics

have made TPU one of the most extensively adopted materials for wearable robotics, soft grippers, biomedical actuators, locomotion systems, and adaptive soft robotic devices.

Despite these advantages, the airtightness performance of TPU-based actuators varies considerably due to the inherent material behavior of TPU, as discussed in Section 4.1. Softer TPU grades such as TPU 60A and 70A generally improve actuator compliance and deformation capability but may also increase viscoelastic creep, pressure instability, and dimensional deformation during cyclic pneumatic loading [147,148].

Several studies have additionally demonstrated that TPU formulations, printing parameters, and filament-processing conditions strongly influence interlayer bonding strength and permeability behavior in FFF-printed structures [149–151]. Drying procedures, elevated nozzle temperatures, reduced print speeds, optimized raster overlap, and surface-sealing approaches are therefore commonly employed to improve pressure retention and reduce leakage-related defects in TPU soft pneumatic actuators.

Recent advances in TPU-based AM have further expanded the capabilities of soft robotic systems through pellet-based extrusion [152], multi-material printing, embedded-sensing integration, and flexible membrane fabrication. These developments continue to improve the scalability, customization, and multifunctionality of TPU-based soft robotic actuators while simultaneously emphasizing the importance of leakage-aware manufacturing and airtightness optimization.

### 5.2. Photopolymer Elastomers

Photopolymer elastomers used in stereolithography (SLA) [153], digital light processing (DLP) [154–157], and vat photopolymerization [158] systems can provide smoother surfaces, finer geometric resolution, and lower initial porosity than conventional FFF-printed TPU structures. Because these fabrication methods rely on photopolymer curing rather than layer-wise thermoplastic extrusion, the resulting structures often exhibit improved dimensional accuracy and reduced surface roughness, which can enhance initial airtightness performance.

Studies have demonstrated the potential of vat photopolymerization for fabricating high-resolution soft robotic structures, microfluidic systems, flexible membranes, and small-scale pneumatic actuators [159,160]. However, many soft photopolymer materials exhibit reduced elongation, lower fatigue resistance, long-term aging, and UV-induced embrittlement compared with silicone elastomers and TPU-based systems. These limitations reduce their suitability for highly deformable cyclic pneumatic applications involving repeated large-strain loading conditions.

### 5.3. Emerging Elastomeric and Composite Materials

Emerging materials for airtight soft pneumatic actuators include bio-based elastomers [161], self-healing polymers [162], fiber-reinforced elastomers [163], soft composite resins [164], nanocomposite materials [165], and multilayer barrier structures [166], which show significant promise for improving airtightness and durability. Composite elastomer systems incorporating reinforcement fibers, nanofillers, graphene derivatives, and hybrid material architectures have demonstrated the potential to improve stiffness tunability, permeability resistance, and structural durability [167,168]. Barrier-layer composite structures can additionally reduce gas diffusion through the actuator wall while preserving actuator flexibility and deformation capability. However, interface mismatch, material incompatibility, thermal expansion differences, and fabrication complexity remain significant challenges for multi-material pneumatic systems.

Self-healing elastomeric materials have also emerged as promising candidates for resilient soft robotic systems, enabling partial or complete recovery from cuts, punctures,

tears, and other macroscopic damage. Fused filament fabrication of thermoreversible self-healing elastomeric polymers has enabled the development of adaptive soft robotic structures capable of recovering from mechanical damage while supporting complex actuator geometries and repeated damage-healing cycles [169–171]. These materials may significantly improve the durability and operational lifetime of future airtight pneumatic soft robotic systems.

Advanced additive manufacturing approaches such as the InFoam method have demonstrated the capability to fabricate graded porous soft fluidic actuators with programmable stiffness, deformation behavior, and fluid transport characteristics by controlling porosity during printing, enabling adaptive bending, twisting, and contraction behaviors in soft robotic systems [172]. A study demonstrated that a nine-chamber additively manufactured PneuNet actuator with graded porous infill achieved approximately 82° bending under an applied pressure of 8 bar, although airtightness and post-processing remained major challenges for reliable pneumatic performance [173].

Multiscale-engineered ionic-conductive elastomer paints have enabled direct, conformal manufacturing of multilayer soft ionotronic systems on complex three-dimensional (3D) multi-material surfaces through brushing, printing, dipping, and spin-coating processes, while maintaining tailorable mechanical properties, conformal adaptability, and functional integration capabilities [174].

Although emerging elastomeric and composite materials demonstrate considerable promise for next-generation soft robotics, long-term pneumatic cycling data, leakage characterization, environmental stability analysis, and standardized airtightness evaluation remain comparatively limited. Consequently, additional studies are required to fully evaluate the long-term reliability and scalability of these advanced material systems for airtight soft pneumatic actuators. Table 1 summarizes the major material systems used for soft pneumatic actuator fabrication, highlighting their advantages, airtightness limitations, mitigation strategies, and typical application areas.

**Table 1.** Comparison of material systems used for soft pneumatic actuator fabrication.

| Material System                              | Key Advantages                                                            | Airtightness Limitations                                                               | Typical Mitigation                                                                                        | Suitability                                                              |
|----------------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| TPU filaments<br>[149–151]                   | Flexible, durable, low-cost, and compatible with desktop FFF systems      | Interlayer voids, moisture-induced porosity, viscoelastic creep, and semi-permeability | Filament drying, elevated nozzle temperature, reduced print speed, optimized overlap, and surface coating | Rapid prototyping, wearable robotics, and customized pneumatic actuators |
| Silicone elastomers<br>[175–177]             | Excellent compliance, fatigue resistance, and intrinsic airtightness      | Requires molding, bonding, curing, and limited internal geometric complexity           | Careful mold design, bonding optimization, and controlled curing                                          | Reliable soft pneumatic systems and high-cycle actuators                 |
| Photopolymer elastomers<br>[159,160]         | Smooth surfaces, high resolution, and reduced initial porosity            | Aging, brittleness, UV sensitivity, and limited fatigue resistance                     | Resin optimization, post-curing control, and structural reinforcement                                     | Microfluidics, miniature actuators, and precision soft structures        |
| Composite elastomers<br>[167,168,178]        | Tailorable stiffness, improved barrier properties, and multifunctionality | Interface mismatch, fabrication complexity, and material incompatibility               | Hybrid design optimization and interface engineering                                                      | Advanced multifunctional and reinforced soft actuators                   |
| Self-healing elastomers<br>[169–171,179–182] | Potential damage recovery, extended lifetime, and adaptive functionality  | Limited pneumatic validation and long-term cycling data                                | Material optimization and repeated healing-cycle evaluation                                               | Future resilient and self-recoverable soft robotic systems               |

Material selection plays a critical role in determining airtightness reliability, cyclic durability, deformation capability, and long-term operational stability in pneumatic soft robotic systems. While TPU remains the most widely adopted material for FFF-based

actuator fabrication, elastomeric and composite materials continue to expand the design space for next-generation airtight soft robotic actuators.

The comparative analysis demonstrates that no single material simultaneously satisfies the requirements for flexibility, durability, and long-term airtightness. TPU offers significant advantages for monolithic FFF fabrication and rapid prototyping, whereas silicone generally provides superior intrinsic sealing performance.

## 6. Additive Manufacturing and Fabrication Strategies

This section evaluates additive manufacturing technologies from a process perspective, emphasizing their influence on fabrication quality, airtightness, scalability, and manufacturing capability.

The fabrication method plays a critical role in determining the airtightness, mechanical performance, geometric complexity, and overall functionality of soft pneumatic actuators. Both conventional molding techniques and emerging additive manufacturing approaches have been extensively explored to address the diverse requirements of soft robotic systems. Table 2 summarizes the principal fabrication strategies reported in the literature, highlighting their strengths, airtightness characteristics, limitations, and typical applications. The comparison illustrates the trade-offs between manufacturing flexibility, sealing performance, and design complexity that must be considered when selecting an appropriate fabrication approach for soft pneumatic actuators.

**Table 2.** Additive manufacturing and fabrication strategies for soft pneumatic actuators.

| Fabrication Method                  | Primary Strengths                                                      | Airtightness Tendency                   | Major Limitations                                                            | Typical Applications                                                     |
|-------------------------------------|------------------------------------------------------------------------|-----------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Silicone molding<br>[183,184]       | Excellent compliance, flexibility, and intrinsic sealing               | High                                    | Multi-step fabrication, tooling dependency, and limited geometric complexity | Reliable soft pneumatic actuators and high-cycle systems                 |
| FFF/FDM TPU<br>[185]                | Low cost, rapid prototyping, monolithic fabrication, and accessibility | Low to moderate without post-processing | Interlayer voids, anisotropy, and process-induced porosity                   | Rapid prototyping, wearable robotics, and customized actuator geometries |
| SLA/DLP elastomers<br>[186]         | Smooth surfaces, high resolution, and reduced visible porosity         | Moderate to high initially              | Material aging, brittleness, and limited fatigue resistance                  | Miniaturized actuators, microfluidics, and precision soft structures     |
| Multi-material AM<br>[187–189]      | Integrated functions, embedded sensing, and multifunctionality         | Variable                                | Interfacial delamination and material incompatibility                        | Sensorized and multifunctional soft robotic systems                      |
| Hybrid molding-printing<br>[79,190] | Balances geometric freedom and sealing performance                     | Moderate to high                        | Increased process complexity and fabrication coordination                    | Advanced research prototypes and high-performance soft actuators         |

### 6.1. Fused Filament Fabrication and Pellet-Based Extrusion

FFF remains the dominant AM method for TPU-based soft pneumatic actuator fabrication because of its accessibility, rapid prototyping capability, compatibility with flexible materials, and support for monolithic pneumatic geometries [191–193]. FFF enables direct, layer-by-layer fabrication of embedded pneumatic chambers, flexible membranes, soft hinges, and multifunctional actuator structures without the need for molds or complex assembly processes. These advantages have made FFF one of the most widely adopted fabrication approaches in soft robotics.

Recent developments in fused granulate fabrication (FGF) have introduced scalable alternatives to conventional filament-based FFF by employing screw-driven extrusion of thermoplastic pellets for soft actuator manufacturing. Optimized pellet-extrusion strategies have demonstrated improved printing stability, enhanced airtightness, and durable

soft robotic structures with mechanical performance comparable to silicone elastomers and operational lifetimes exceeding 100,000 bending cycles [194]. Pellet-based additive manufacturing of ultra-soft thermoplastic elastomers (TPEs) has additionally enabled the fabrication of highly deformable airtight membranes capable of sustaining extreme elongation and large bending deformation in pneumatic soft actuators [195]. The integration of soft TPE pellet extrusion with multimaterial printing has further demonstrated lightweight actuator structures, conformal gripping systems, embedded sensing functionality, and adaptive soft robotic behavior.

AM platforms demonstrated the capability to fabricate ultra-flexible soft robotic systems with embedded fluidic logic using consumer-level printing technologies and unconventional printing orientations. These scalable fabrication approaches significantly expand the range of printable geometries for soft robots, improve manufacturing accessibility, and support standardized production workflows for pneumatic soft robotic systems [196].

Overall, FFF and pellet-based extrusion technologies continue to provide highly accessible and scalable manufacturing solutions for soft pneumatic actuators while simultaneously emphasizing the importance of leakage-aware printing strategies and airtightness optimization.

To complement the qualitative discussion, Table 3 summarizes representative FFF-printed TPU soft pneumatic actuator studies that explicitly report key fabrication parameters affecting airtightness, including TPU hardness, printing conditions, pressure range, and the corresponding pressure-retention performance. Because the published literature reports fabrication parameters with varying levels of detail, only studies providing sufficient experimental information are included. The comparison highlights the influence of processing parameters on airtightness while illustrating the current lack of standardized reporting across the literature.

**Table 3.** Representative FFF-printed TPU soft pneumatic actuator studies reporting TPU hardness, key fabrication parameters, pressure conditions, and their corresponding pressure-retention outcomes. NR = Not Reported.

| Reference | TPU-Shore           | Printing Parameters                                                                                                                                                          | Pressure Range | Pressure-Retention Outcome                                                                                      |
|-----------|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|-----------------------------------------------------------------------------------------------------------------|
| [197]     | TPU 95A, 80A LF     | Layer height: 0.15 mm; Infill: 100%;<br>Nozzle diameter: 0.4 mm;<br>Print speed: 25 mm/s;<br>Bed temperature: 60 °C;<br>Nozzle temperature: 225 °C                           | 0.4 MPa        | Maintained airtightness down to 1.0 mm wall thickness; line width was the primary factor governing air leakage. |
| [198]     | TPU                 | Layer height: 0.1 mm; Infill: 100%;<br>Wall thickness: 1.2 mm;<br>Nozzle diameter: 0.4 mm;<br>Print speed: 30 mm/s;<br>Bed temperature: 60 °C;<br>Nozzle temperature: 220 °C | 0.5 MPa        | NR                                                                                                              |
| [199]     | TPU                 | Wall thickness: 1, 1.2, 1.4, 1.6 mm                                                                                                                                          | 0.05 MPa       | Enhanced airtightness at a wall thickness of 1.6 mm at 30 kPa.                                                  |
| [200]     | FilaFlex 60A        | Layer height: 0.16 mm; Infill: 100%;<br>Wall thickness: 1.2 mm;<br>Print speed: 10 mm/s;<br>Bed temperature: 60 °C;<br>Nozzle temperature: 220 °C, Pattern: Zigzag           | 0.15 MPa       | NR                                                                                                              |
| [60]      | TPU 70, 65, 74, ... | Layer height: 0.2 mm; Infill: 100%;<br>Bed temperature: 60 °C;<br>Nozzle diameter: 0.4 mm;<br>Nozzle temperature: 220 °C, Pattern: Linear                                    | 0.5 MPa        | NR                                                                                                              |

### 6.2. Vat Photopolymerization

Vat photopolymerization techniques, including stereolithography (SLA), digital light processing (DLP), and related photopolymer-curing methods, fabricate soft structures through localized photopolymer solidification and can achieve smoother surfaces, finer geometric resolution, and lower visible porosity than conventional FFF-based fabrication [201–205]. Because these processes rely on photopolymer curing rather than thermoplastic extrusion, the resulting structures often exhibit improved dimensional accuracy and more uniform surface morphology.

Studies have demonstrated the potential of vat photopolymerization for fabricating high-resolution soft robotic structures [206,207], flexible membranes [208], microfluidic systems [209], and miniature pneumatic actuators [210]. The ability to fabricate complex internal channels and geometrically precise pneumatic architectures makes these approaches attractive for biomedical soft robotics, precision actuation systems, and miniaturized fluidic devices [211].

Despite these advantages, vat-photopolymerized elastomers often exhibit limitations in fatigue resistance, long-term elasticity, cyclic durability, and material aging [212]. Many soft photopolymers undergo progressive embrittlement, stiffness increase, and degradation under repeated cyclic deformation or prolonged environmental exposure. Consequently, although vat photopolymerization can initially provide improved surface quality and reduced visible porosity, long-term airtightness reliability and cyclic durability remain important challenges for highly deformable pneumatic actuator systems.

### 6.3. Multi-Material and Hybrid Manufacturing

Multi-material AM significantly expands the design space of soft pneumatic actuators by enabling the integration of compliant chambers, rigid connectors, reinforcement regions, embedded sensing elements, and multifunctional interfaces within a single fabrication workflow [213]. These approaches improve structural adaptability, actuator functionality, and system-level integration while supporting the development of sensorized, bioinspired, and multifunctional soft robotic systems [187–189]. However, differences in stiffness, thermal expansion, curing behavior, and interfacial adhesion between adjacent materials may introduce new leakage pathways and interfacial delamination risks within pneumatic systems.

Pneumatic-tendon-coupled actuator systems have additionally demonstrated that combining pneumatic compliance with tendon-driven motion control can improve controllability, variable stiffness, and energy efficiency in untethered soft robotic systems. Interconnected pneumatic actuator architectures with integrated air circuits and compact pumping systems have shown improved multifunctionality, reduced actuation energy consumption, and enhanced system integration capability for complex soft robotic behaviors [214].

Hybrid manufacturing strategies combining additive manufacturing and molding techniques have therefore emerged as promising approaches for balancing geometric flexibility with improved sealing performance. Hybrid molding-printing approaches can combine the geometric freedom of additive manufacturing with the superior airtightness and compliance of molded elastomeric structures [79,190].

Overall, the reviewed fabrication approaches demonstrate that filament-based FFF remains the most accessible and versatile technology for producing customized soft pneumatic actuators because of its low cost, design flexibility, and rapid prototyping capability. However, fabrication-induced defects, material compatibility, interfacial reliability, and long-term airtightness continue to limit its performance. Although alternative manufacturing methods generally provide improved sealing performance, they often require greater fabrication complexity, higher cost, or reduced design flexibility. Consequently, improving

airtightness within the FFF process remains a key research priority for developing reliable and scalable soft robotic systems.

## 7. Post-Processing and Airtightness Enhancement Strategies

### 7.1. Surface Coatings and Composite Sealing Approaches

Surface coating is one of the post-processing approaches for improving airtightness in FFF-printed soft pneumatic actuators because it can reduce surface-connected porosity, seal microvoids, and improve pressure retention capability [215]. Silicone-based coatings [216] are particularly attractive for pneumatic soft robotic systems because they remain compliant after curing and can penetrate shallow surface defects while preserving actuator flexibility and deformation capability. By forming a conformal elastomeric barrier layer, silicone coatings can significantly reduce leakage through superficial interlayer discontinuities and porous regions without substantially increasing structural stiffness.

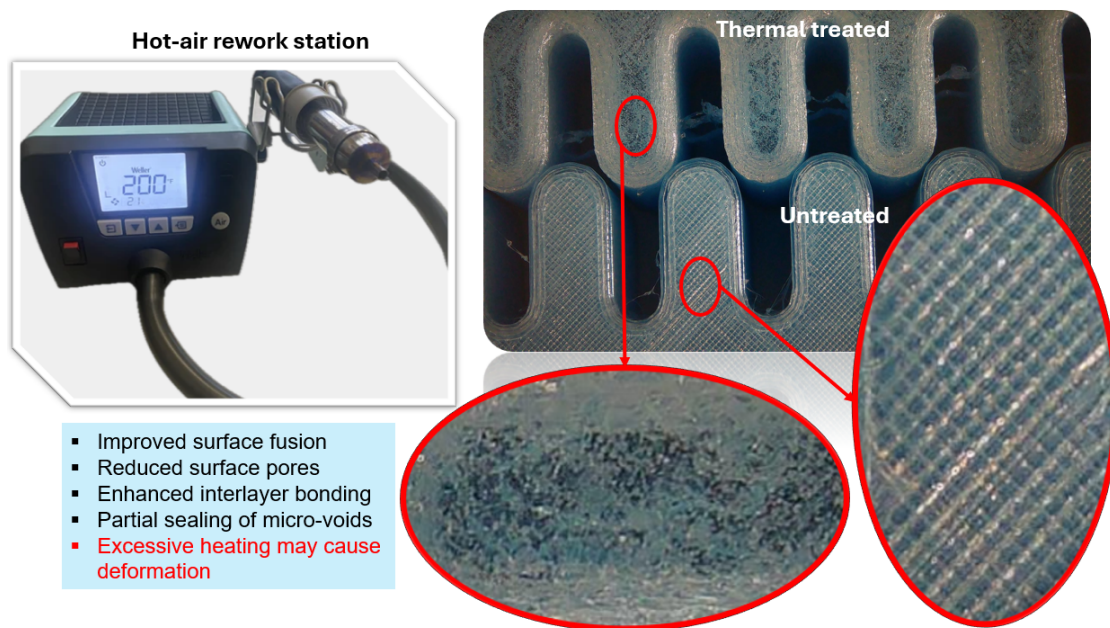
Epoxy-based sealing strategies can provide stronger impermeable barriers and improved leakage reduction compared with compliant silicone coatings; however, the rigid nature of epoxy materials can increase actuator stiffness, reduce bending deformation, and introduce crack formation during repeated cyclic loading [217]. Resin infiltration techniques have additionally been investigated for sealing deeper porous networks and internal micro-defects within printed TPU structures.

Hybrid soft pneumatic actuator architectures combining silicone bladders, extensible anisotropic fabrics, and TPU-based structures have further demonstrated improved airtightness, reduced stiffness, and lower actuation pressure requirements compared with conventional single-material actuator systems [20]. In these composite architectures, silicone layers serve as hermetic sealing barriers, while fabric-based constraint skins enhance deformation control, structural adaptability, and mechanical efficiency. These hybrid systems have demonstrated large bending and torsional deformation capability together with improved pneumatic efficiency and structural reconfigurability for wearable and high-force soft robotic applications. Fabric reinforcement has additionally demonstrated the ability to improve force output, bending stability, and structural durability in soft pneumatic actuator systems [218].

### 7.2. Localized Thermal Surface Reflow

Localized thermal post-processing using controlled hot-air exposure has emerged as a practical and low-cost method for improving airtightness in FFF-printed soft pneumatic actuators [219]. In this approach, as illustrated in Figure 8, a surface-mounted hot-air rework tool or localized thermal source applies controlled heat to the external actuator surface, partially reflowing the outer filament layers and promoting additional interfacial polymer diffusion. This localized thermal reflow can smooth surface discontinuities, improve inter-road fusion, and reduce surface-connected microvoids responsible for pressure leakage.

Unlike rigid coating strategies, controlled thermal reflow can preserve the inherent flexibility and compliance of TPU structures when properly optimized. The effectiveness of thermal post-processing depends strongly on treatment temperature, exposure duration, nozzle distance, airflow rate, wall thickness, and local actuator geometry. Moderate thermal exposure can improve surface sealing and pressure retention, whereas excessive heating may produce wall thinning, dimensional distortion, chamber collapse, thermal degradation, or geometric instability in highly compliant actuator regions.



**Figure 8.** Localized hot-air thermal treatment of TPU soft actuator surfaces. Partial surface reflow improves inter-road fusion and reduces surface-connected microvoids, whereas excessive heating may deform thin compliant walls.

### 7.3. Sealing Trade-Offs and Reliability Considerations

Each airtightness enhancement strategy involves trade-offs among pressure retention, flexibility, durability, manufacturability, and system complexity. Silicone coatings maintain actuator compliance, whereas epoxy-based sealing provides superior barrier performance at the expense of increased stiffness [220]. Resin infiltration can seal internal porosity but may alter actuator deformation behavior.

Thermal reflow offers a low-cost sealing approach but requires careful temperature control to avoid structural distortion. Leakage at tubing interfaces, pressure ports, and bonded joints can also significantly affect overall system performance. Therefore, the optimal sealing strategy depends on actuator geometry, operating conditions, deformation requirements, and manufacturing constraints. Table 4 summarizes representative post-processing and airtightness enhancement methods for FFF-printed soft pneumatic actuators.

**Table 4.** Post-processing strategies for airtight FFF-printed soft actuators.

| Method                                 | Primary Function                                         | Advantages                                                | Limitations                                                 | Typical Applications                         |
|----------------------------------------|----------------------------------------------------------|-----------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------|
| Silicone coating [221]                 | Flexible conformal barrier layer                         | Maintains compliance and seals surface-connected pores    | Coating thickness variability and curing inconsistency      | Dynamic soft pneumatic actuators             |
| Epoxy sealing [222]                    | Rigid impermeable surface barrier                        | Strong leakage reduction and improved pressure retention  | Increases stiffness and may crack during cyclic deformation | Static or low-deformation pneumatic regions  |
| Resin infiltration [223]               | Seals internal porous networks                           | Can penetrate deeper micro-defects                        | May reduce flexibility and alter deformation behavior       | Porous or rough printed surfaces             |
| Thermal reflow [219]                   | Partial remelting of the outer TPU surface               | Low cost and no additional material requirement           | Risk of overheating and dimensional distortion              | Localized leakage mitigation                 |
| Connector sealing [197]                | Reduces interface-related leakage                        | Addresses common macroscopic leakage sites                | Requires repeatable assembly and interface control          | Tubing ports and pneumatic interfaces        |
| Hybrid silicone–fabric structures [20] | Combines compliant sealing with structural reinforcement | Improved airtightness, adaptability, and force capability | Increased fabrication complexity                            | Wearable and high-force soft robotic systems |

#### 7.4. Rapid and Scalable Soft Actuator Manufacturing

Recent rapid-manufacturing strategies based on thermoplastic pouch processing combined with vacuum-assisted sealing and laser cutting have demonstrated low-cost and scalable fabrication of inflatable soft pneumatic actuators with programmable deformation behavior and fast response characteristics [224]. In these systems, vacuum-assisted processing removes trapped air gaps between thermoplastic layers prior to sealing, thereby improving sealing consistency and geometric precision during fabrication.

Compared with highly compliant silicone elastomers, thermoplastic-based actuator structures can reduce deformation losses and improve energy-transfer efficiency during pneumatic actuation. Finite element (FE)-assisted [225] inverse-design methodologies have additionally enabled programmable deformation control and the fabrication of adaptable soft robotic systems, including crawlers [226], swimmers [227], and soft grippers [227,228]. These developments demonstrate the growing importance of scalable manufacturing strategies that balance airtightness, deformation control, fabrication speed, and low-cost production for next-generation soft robotic systems.

Overall, post-processing and airtightness enhancement strategies remain essential for improving the pressure retention capability, cyclic durability, and operational reliability of FFF-printed soft pneumatic actuators. Future developments will likely integrate intelligent process monitoring, adaptive post-processing, multifunctional composite architectures, and scalable manufacturing workflows to further improve the reliability and manufacturability of airtight soft robotic systems.

### 8. Experimental Insights

The objective of this section is to demonstrate representative leakage behavior in FFF-printed soft pneumatic actuators and to correlate literature-reported leakage mechanisms with experimentally observed pressure-decay behavior, bubble testing, and microscopy-based defect characterization. The presented results correspond to a representative experimental validation intended to qualitatively support the leakage mechanisms discussed throughout this review rather than provide a statistical assessment of process variability.

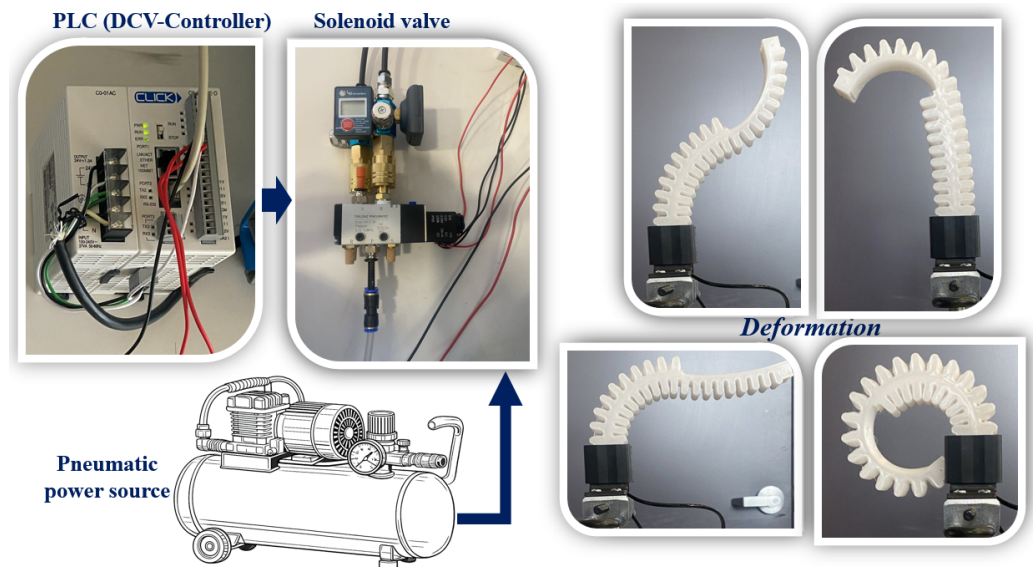
#### 8.1. Experimental Framework

As representative validation of the leakage mechanisms discussed in this review, an asymmetrical multi-chamber TPU soft-bending actuator was fabricated using fused filament fabrication (FFF) (Figure 9). Printing was performed using Sovol SV08 and Creality K2 systems. Surface morphology and potential leakage defects were qualitatively examined using a Tomlov digital microscope.

As discussed in Section 7.2, localized hot-air treatment was applied using a Weller® hot-air station [229] to improve interfacial fusion and reduce surface-connected leakage pathways. Representative printing parameters included 100% infill, a nozzle temperature of 230 °C, a bed temperature of 30 °C, a layer height of 0.2 mm, and a print speed of 25 mm/s. A solenoid-operated directional control valve controlled by a CLICK PLC [230] regulated airflow to the actuator chambers during experimental evaluation.

#### 8.2. Representative Leakage Observations

Representative observations demonstrated that nominal 100% infill TPU actuators can still exhibit substantial pneumatic leakage despite appearing visually dense after fabrication. These findings support previous studies indicating that full infill does not necessarily eliminate microscopic interlayer voids, surface-connected porosity, seam discontinuities, or incomplete filament fusion within FFF-printed structures.



**Figure 9.** Experimental setup and pneumatic bending deformation of the TPU soft actuator.

Post-processing and sealing treatments significantly reduced observed pressure loss, indicating that many leakage pathways are associated with near-surface interconnected defects rather than large macroscopic structural discontinuities. Localized thermal surface treatment additionally demonstrated the potential to reduce leakage through partial reflow of outer filament layers and improved inter-road fusion.

Figure 10 illustrates that visible air bubble formation was observed near interfacial regions and printed surface boundaries, confirming the presence of interconnected leakage channels within the untreated actuator structure.



**Figure 10.** Bubble-leakage testing of the FFF-printed TPU pneumatic actuator during pressurization.

### 8.3. Pressure-Decay Characterization and Energy Implications

Pressure-decay experiments were conducted to evaluate the leakage behavior of the FFF-printed TPU actuator and to quantify the effect of localized heat treatment on airtightness. The connector-line baseline was first established by sealing the outlet port, pressurizing the system to approximately 93.4 psi, and subsequently closing the shutoff valve. Consequently, the pressure loss measured in the baseline configuration represents the inherent leakage associated with the pneumatic tubing, fittings, and connector hardware. The untreated and heat-treated actuators were then tested under identical sealed conditions.

The pressure-retention ratio was calculated according to Equation (1):

$$R_p(t) = \frac{P_t}{P_0} \times 100, \quad (1)$$

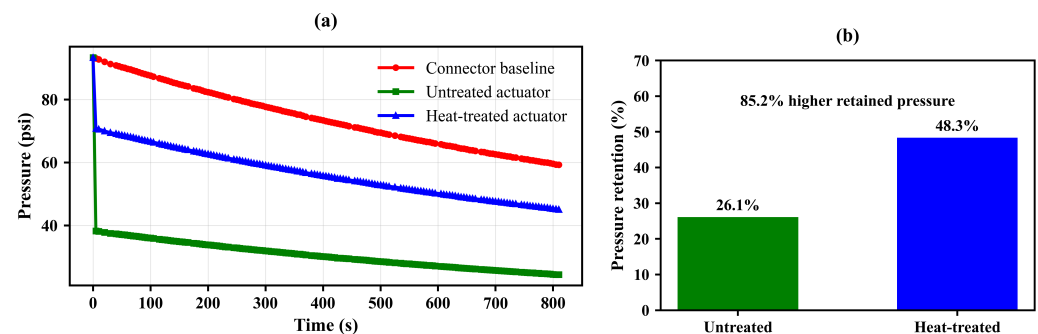
where  $P_0$  denotes the initial pressure and  $P_t$  represents the pressure measured at time  $t$ .

The corresponding pressure-decay percentage was determined using Equation (2):

$$D_p(t) = \frac{P_0 - P_t}{P_0} \times 100, \quad (2)$$

where  $D_p(t)$  represents the normalized pressure loss as a function of time.

Figure 11a presents the measured pressure-decay response of the connector baseline, untreated actuator, and heat-treated actuator. The connector-line baseline exhibited the slowest pressure decrease, confirming that leakage associated with the pneumatic hardware and fittings was relatively small. In contrast, the untreated actuator experienced rapid pressure loss, indicating the presence of significant leakage pathways originating from fabrication-induced defects such as inter-road gaps, incomplete filament fusion, and interlayer voids.



**Figure 11.** Pressure-decay characterization of the connector baseline, untreated actuator, and heat-treated actuator. (a) Pressure decay measured during the 810 s test interval. (b) Pressure retention after 13.5 min. The experiments were terminated after 810 s; consequently, the measured pressures do not represent steady-state values and would continue to decrease toward atmospheric pressure if the test duration were extended.

The experiments were terminated after 810 s; therefore, the final pressures should not be interpreted as steady-state values. Instead, the pressure would be expected to continue decreasing toward atmospheric pressure if the test duration were extended. At the end of the measurement period, the connector baseline retained 59.3 psi, corresponding to 63.5% pressure retention. In comparison, the untreated actuator retained only 24.38 psi, corresponding to 26.1% pressure retention. Following localized heat treatment, the retained pressure increased to 45.15 psi, corresponding to 48.3% pressure retention.

As shown in Figure 11b, the heat-treated actuator retained substantially more pressure than the untreated actuator throughout the experiment. At 810 s, the heat-treated actuator retained approximately 85.2% more pressure than the untreated actuator. Moreover, the pressure loss decreased from 73.9% for the untreated actuator to 51.7% for the heat-treated actuator, corresponding to a reduction of approximately 30.1% in pressure decay. This improvement is attributed to localized thermal reflow of TPU, which partially seals surface-connected defects and enhances inter-road bonding.

#### 8.4. AI-Assisted Predictive Frameworks and Future Research Directions

Artificial intelligence (AI), machine learning (ML), and digital-twin frameworks are emerging as promising approaches for predictive leakage monitoring, intelligent process optimization, and real-time reliability assessment in soft pneumatic actuator systems [231–233]. Unlike purely analytical approaches, data-driven methods can capture nonlinear relationships among fabrication parameters, actuator geometry, microstructural defects, leakage behavior, and pneumatic performance.

Potential machine-learning input variables include nozzle temperature, print speed, layer height, extrusion multiplier, raster orientation, wall thickness, chamber curvature, cooling conditions, pressure-cycle history, and microscopy-derived porosity metrics [234–236]. Model outputs may include leakage rate, pressure-decay constant, permeability estimation, airtightness classification, and probability of actuator failure under cyclic loading conditions.

Soft materials and flexible devices have increasingly enabled integrated sensorimotor functions in soft robotic systems through combined sensing, actuation, structural adaptability, artificial intelligence, and bioinspired control strategies [237]. Machine-learning-based frameworks have additionally demonstrated effective real-time leakage prediction in pneumatic actuators using pressure-decay and cyclic-testing data, with K-Nearest Neighbors (KNN) and Multilayer Perceptron (MLP) models achieving high leakage-classification accuracy [238]. Advanced defect-monitoring frameworks further emphasize multimodal sensing, deep learning, diffusion models, and digital-twin-enabled additive manufacturing for intelligent soft robotic fabrication [61].

Integrated pressure, strain, and flow sensors can further support real-time leakage detection and adaptive pneumatic regulation, while dual-loop PID and fractional-order PID controllers have demonstrated improved pressure stability and reduced oscillatory behavior in pneumatic systems [239]. Solenoid valve-driven soft pneumatic systems additionally exhibit pressure-dependent nonlinearities, transient switching behavior, and modulation-dependent control characteristics that influence pneumatic regulation accuracy [240]. Electronics-free pneumatic sensory architectures have also demonstrated autonomous sensing and multifunctional pneumatic operation while reducing overall system complexity [241].

Despite these advances, several challenges remain unresolved in airtightness reliability, scalable manufacturing, intelligent monitoring, and long-term pneumatic durability. Standardized airtightness testing methodologies remain limited, particularly for pressure-decay testing, cyclic loading evaluation, leakage-rate normalization, and environmental conditioning. Long-term airtightness degradation under repeated inflation cycles, sustained pressure loading, and environmental aging also remains insufficiently investigated.

Future research is expected to further emphasize scalable leakage-aware manufacturing, energy-efficient actuation, intelligent bioinspired systems, sustainable materials, embedded sensing, and adaptive underwater soft robotic platforms. Bioinspired pneumatic architectures have demonstrated improved motion efficiency and reduced energy consumption through optimized deformation and gait-control strategies [242,243]. Emerging systems integrating multifunctional sensing, programmable materials, AI-assisted control, and advanced additive manufacturing are expected to accelerate the development of adaptive next-generation soft robotic technologies [244–248].

Overall, the reviewed studies demonstrate that AI-assisted monitoring is transitioning from post-process defect identification toward real-time process control and predictive manufacturing. However, relatively few studies have specifically targeted leakage prediction in FFF-printed soft pneumatic actuators, highlighting an important opportunity for future research.

### 8.5. Limitations

Although this review provides a comprehensive synthesis of the literature on airtight FFF-printed soft pneumatic actuators, several limitations should be acknowledged. Only English-language publications were considered, which may have excluded relevant studies published in other languages. In addition, substantial variations in actuator geometry, material composition, fabrication parameters, leakage metrics, and experimental

methodologies limited direct quantitative comparisons across studies. The representative experiments included in this review are intended to qualitatively support the literature synthesis rather than provide statistically rigorous experimental validation. Finally, because additive manufacturing and soft robotic technologies continue to evolve rapidly, recently published studies may not be fully represented within the review period. Nevertheless, the inclusion of 248 studies provides a comprehensive overview of the current state of the art, identifies key leakage mechanisms and airtightness challenges, and highlights future research opportunities for FFF-printed soft pneumatic actuators.

## 9. Conclusions

This review comprehensively examined the major airtightness challenges associated with FFF-printed TPU soft pneumatic actuators and demonstrated that leakage behavior is governed by the coupled effects of material properties, additive manufacturing parameters, interlayer bonding quality, geometric design, and interface sealing. Although FFF offers significant advantages, including low-cost fabrication, rapid prototyping, and high geometric flexibility, process-induced porosity, seam discontinuities, and incomplete filament fusion remain the primary causes of pneumatic leakage and reduced long-term reliability.

The reviewed literature indicates that achieving reliable airtight performance requires an integrated, leakage-aware design strategy that combines optimized material selection, printing parameters, geometric design, connector sealing, and post-processing techniques such as compliant surface coatings and localized thermal reflow. Representative experimental observations further supported the literature by demonstrating the influence of interfacial defects, pressure-leakage pathways, and hot-air treatment on actuator sealing performance. In addition, emerging AI-assisted monitoring, predictive leakage modeling, and digital-twin frameworks show considerable promise for intelligent defect detection, process optimization, and leakage-aware manufacturing. The principal findings of this review are summarized as follows:

- Interlayer voids, seam discontinuities, and porous microstructures are the dominant leakage sources in FFF-printed TPU soft pneumatic actuators.
- Airtightness is governed by the combined effects of material properties, processing parameters, and actuator geometry rather than infill density alone.
- Localized thermal reflow and compliant surface coatings can significantly improve pressure retention while preserving actuator flexibility.
- Embedded sensing, AI-assisted monitoring, and digital-twin technologies provide promising pathways for predictive leakage assessment and intelligent manufacturing.
- Standardized leakage characterization methods, pressure-retention metrics, and long-term durability evaluations remain limited and should be established to enable meaningful comparisons across future studies.

Overall, airtightness should be considered a fundamental design requirement rather than a post-fabrication consideration in FFF-printed TPU soft pneumatic actuators. Future research should focus on standardized leakage evaluation protocols, scalable leakage-aware manufacturing strategies, intelligent sensing integration, and predictive modeling to improve the reliability, durability, and industrial adoption of next-generation soft robotic systems.

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## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                  |
|------|----------------------------------|
| AI   | Artificial Intelligence          |
| AM   | Additive Manufacturing           |
| CAD  | Computer-Aided Design            |
| DLP  | Digital Light Processing         |
| FDM  | Fused Deposition Modeling        |
| FE   | Finite Element                   |
| FFF  | Fused Filament Fabrication       |
| FGF  | Fused Granulate Fabrication      |
| KNN  | K-Nearest Neighbors              |
| LRC  | Liquid Rope Coiling              |
| ML   | Machine Learning                 |
| PDMS | Polydimethylsiloxane             |
| PID  | Proportional–Integral–Derivative |
| RLP  | Rapid Liquid Printing            |
| SLA  | Stereolithography                |
| TPE  | Thermoplastic Elastomer          |
| TPU  | Thermoplastic Polyurethane       |
| UV   | Ultraviolet                      |

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