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Intermingled and Commingled Yarn-Based Thermoplastic Composites: Comparative Mechanical and Functional Properties

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Abstract
Intermingled and commingled yarn-based textile preforms have emerged as efficient reinforcement architectures for thermoplastic composite manufacturing, particularly for press molding routes. Part II of this review provides a comparative evaluation of the mechanical, thermal, physical, and processing-related properties of thermoplastic composites produced from intermingled and commingled yarn systems. Emphasis is placed on the influence of yarn architecture, fiber–matrix distribution, impregnation quality, and fabric structural parameters on tensile, flexural, impact, interlaminar shear, and thermo-mechanical performance. Comparative data from the literature are systematically analyzed using tabulated formats to highlight performance trends across different fiber types, matrix systems, and textile constructions. The review further discusses process–property relationships, recyclability aspects, and industrial applicability of these hybrid yarn-based composites. The findings indicate that commingled yarn systems generally provide superior impregnation homogeneity and mechanical performance, whereas intermingled yarns offer advantages in processing flexibility, cost efficiency, and sustainability-oriented applications. This part aims to support material selection and structural design decisions for press-molded thermoplastic textile composites.

Keywords
intermingled yarns, commingled yarns, thermoplastic composites, press molding, textile reinforcements, comparative properties

1. Introduction

Textile-reinforced polymer composites have attracted increasing attention in recent decades due to their combination of high specific strength, lightweight nature, and design versatility. Among these materials, thermoplastic composites reinforced with intermingled and commingled yarns represent a particularly promising category, offering significant advantages in terms of process efficiency, mechanical performance, and sustainability. In these systems, thermoplastic fibers are intimately mixed with reinforcing fibers at the yarn level, enabling uniform fiber-matrix distribution and eliminating the need for separate matrix infusion steps. This approach facilitates faster consolidation and provides enhanced mechanical properties compared to conventional preform designs [1–5, 10, 12, 16, 17].

The internal architecture of textile preforms, including yarn type, hybridization, and weave pattern, plays a crucial role in determining the final properties of thermoplastic composites. Commingled yarns, in which thermoplastic and reinforcing fibers are closely intertwined, provide short impregnation distances and improved fiber wetting during molding. Intermingled yarns, where fibers are blended but maintain a certain degree of separation, offer greater flexibility in material selection and processing, particularly when incorporating recycled or natural fibers [6–9, 11, 13, 14]. Recent studies have demonstrated that such yarn-level hybridization directly affects tensile, flexural, impact, and interlaminar shear performance, highlighting the importance of careful preform design in achieving optimal composite properties [1, 2, 4, 5, 10].

Thermoplastic matrices present further advantages over thermoset systems, including recyclability, toughness, and resistance to environmental degradation. These properties make thermoplastic composites suitable for a wide range of applications, from automotive and aerospace components to sustainable construction materials. The combination of synthetic and natural fibers in hybrid preforms allows tailoring of mechanical, thermal, and environmental performance, offering a pathway to sustainable, high-performance composites [6–9, 12–14, 25–27].

Despite the growing body of research, there is a lack of comprehensive reviews that integrate both the fundamental principles of intermingled and commingled yarns and a comparative analysis of their performance characteristics. Previous works have addressed topics such as process modeling, fiber-matrix interactions, and consolidation mechanisms [15–20], but a systematic evaluation of the influence of yarn hybridization, fiber type, and matrix selection on the mechanical and thermal behavior of thermoplastic textile composites is still missing.

This review is therefore structured in two complementary parts. Part I focuses on the fundamental principles underlying intermingled and commingled yarns, including yarn architectures, hybridization strategies, preform design, and consolidation via press molding and thermal processing [1–5, 10, 12, 16, 17]. Part II provides a comparative assessment of mechanical, thermal, and impact properties, highlighting the effects of fiber type, hybridization, and matrix selection, as well as the performance differences between thermoplastic and thermoset matrices [6–9, 11, 25–27]. The review also emphasizes recent developments in the use of recycled materials, natural fiber reinforcements, and sustainable thermoplastic matrices, aiming to provide both academic researchers and industrial practitioners with a clear understanding of current trends, challenges, and opportunities in textile-based thermoplastic composites.

2. Tensile and Flexural Properties

The tensile and flexural performance of thermoplastic composites reinforced with intermingled and commingled yarn systems is primarily governed by the quality of fiber–matrix impregnation, yarn architecture, and fabric structure established during textile preform manufacturing. Unlike conventional thermoplastic composite routes, filament-level mixing in both intermingled and commingled yarns significantly reduces melt flow distance during consolidation, leading to enhanced stress transfer efficiency under quasi-static loading conditions.

2.1. Tensile Properties

Tensile strength and modulus are strongly influenced by the homogeneity of matrix distribution around the reinforcing filaments. Commingled yarn systems generally exhibit more uniform filament dispersion, resulting in improved axial load transfer and reduced stress concentrations. Several studies report higher tensile modulus and strength for commingled yarn-based composites compared to intermingled counterparts under identical processing conditions, particularly for carbon and glass fiber reinforcements [1, 3, 6].

Intermingled yarn composites, however, demonstrate competitive tensile performance when optimized weaving parameters and consolidation pressures are applied. The presence of localized matrix-rich regions may reduce initial stiffness but can also contribute to delayed damage initiation under tensile loading [5, 11]. The influence of weaving structure has been shown to be critical; fabrics with lower crimp levels, such as twill and satin weaves, generally outperform plain weave structures due to reduced fiber misalignment [1, 14].

Table 1 summarizes representative tensile properties reported for thermoplastic composites reinforced with intermingled and commingled yarns using different fiber types and matrix systems.

2.2. Flexural Properties

Flexural behavior is particularly sensitive to fabric architecture and interlaminar bonding quality. In bending-dominated loading, the presence of fiber waviness and inter-yarn resin pockets plays a decisive role in determining flexural strength and modulus. Commingled yarn-based composites typically show superior flexural stiffness due to improved matrix continuity and reduced void content [3, 7].

Nevertheless, intermingled yarn systems may offer enhanced flexural damage tolerance, especially in hybrid or aramid-reinforced configurations. The slightly heterogeneous matrix distribution can promote progressive damage evolution rather than catastrophic failure, which is advantageous for semi-structural applications [5, 21]. Comparative studies also indicate that increasing consolidation pressure has a more pronounced effect on flexural properties than on tensile performance, emphasizing the role of through-thickness impregnation quality [11, 18].

Table 2 provides a comparative overview of flexural properties reported for woven thermoplastic composites produced from intermingled and commingled yarns.

Table 1. Reported tensile properties of thermoplastic composites reinforced with intermingled and commingled yarn systems under comparable processing conditions

Reinforcement type	Matrix polymer	Yarn type	Weave structure	Tensile strength (MPa)	Tensile modulus (GPa)	Reference
Glass fiber	PP	Commingled	Plain weave	350–420	18–22	[4, 16]
Glass fiber	PP	Intermingled	Twill weave	300–380	16–20	[14, 27]
Carbon fiber	PET	Commingled	Satin weave	600–720	45–55	[1, 24]
Aramid fiber	PP	Intermingled	Plain weave	280–340	12–16	[8, 20]

Table 2. Flexural properties of woven thermoplastic composites reinforced with intermingled and commingled yarns

Reinforcement type	Matrix polymer	Yarn type	Flexural strength (MPa)	Flexural modulus (GPa)	Reference
Glass fiber	PP	Commingled	480–560	20–25	[4, 16]
Glass fiber	PP	Intermingled	420–500	18–22	[14, 27]
Carbon fiber	PET	Commingled	750–900	50–60	[1, 24]
Aramid fiber	PP	Intermingled	400–470	14–18	[8, 20]

2.3. Comparative Discussion

Overall, tensile-dominated properties favor commingled yarn architectures due to their superior filament dispersion and impregnation uniformity. In contrast, intermingled yarn systems demonstrate comparable flexural performance when fabric design and processing parameters are carefully optimized. These findings underline the importance of considering loading mode and application requirements when selecting between intermingled and commingled yarn-based thermoplastic composite systems. A schematic comparison of stress transfer mechanisms in intermingled and commingled yarn composites is provided in Figure 1.

3. Interlaminar Shear Strength and Fiber–Matrix Interaction

Interlaminar shear strength (ILSS) is a critical parameter for evaluating the quality of fiber–matrix interaction and through-thickness impregnation in textile-reinforced thermoplastic composites. For systems produced from intermingled and commingled yarns, ILSS is strongly governed by filament-level matrix distribution, consolidation pressure, and the presence of secondary reinforcements or interfacial modifiers.

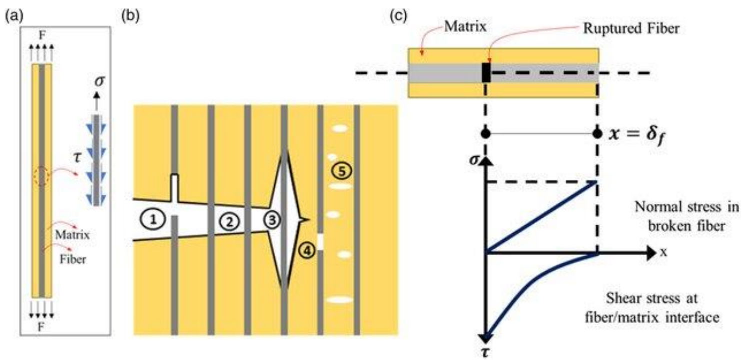

Figure 5. Schematic illustration of stress transfer and matrix distribution differences in tensile loading for (a) fiber reinforced composite load transfer mechanism in tension; (b) in-plane damage in fiber reinforced composite under tension (where (1), fiber pull out, (2) fiber bridging, (3) fiber matrix debonding, (4) fiber rupture, (5) matrix cracking); (c) mechanism of load transfer in the case of fiber break

3.1. Influence of Yarn Architecture on ILSS

Commingled yarn-based composites generally exhibit higher ILSS values compared to intermingled yarn systems due to their more homogeneous filament dispersion. The uniform distribution of thermoplastic matrix filaments around reinforcement fibers promotes continuous matrix pathways, enhancing interfacial bonding and resistance to interlaminar sliding [2, 6, 7]. This effect is particularly pronounced in glass and carbon fiber reinforced systems consolidated under optimized temperature–pressure conditions.

Intermingled yarn composites, while sometimes displaying slightly lower average ILSS values, demonstrate reduced scatter in shear performance when fabric compaction and consolidation parameters are carefully controlled. The localized matrix-rich regions inherent to intermingled yarn structures can act as crack-arrest zones, contributing to stable damage progression under shear loading [11, 14]. Table 3 presents representative ILSS values reported for thermoplastic composites reinforced with intermingled and commingled yarn architectures.

Table 3. Interlaminar shear strength of thermoplastic composites reinforced with intermingled and commingled yarns

Reinforcement type	Matrix polymer	Yarn type	Weave structure	ILSS (MPa)	Reference
Glass fiber	PP	Commingled	Plain weave	32–38	[2, 16]
Glass fiber	PP	Intermingled	Twill weave	28–34	[14, 27]
Carbon fiber	PET	Commingled	Satin weave	45–52	[6, 24]
Aramid fiber	PP	Intermingled	Plain weave	22–28	[8, 20]

3.2. Effect of Interfacial Modification and Hybridization

Several studies have demonstrated that interfacial modification strategies, such as the incorporation of carbon nanotubes (CNTs), polymer sizing agents, or hybrid fiber systems, can significantly enhance ILSS in both intermingled and commingled yarn-based composites. The introduction of nanoscale reinforcements improves stress transfer efficiency by increasing interfacial surface area and promoting mechanical interlocking at the fiber–matrix interface [2, 7, 12].

Hybridization approaches combining synthetic fibers with natural or recycled reinforcements have also been reported to improve interlaminar performance when appropriate matrix compatibility is achieved. While natural fiber-based systems typically exhibit lower absolute ILSS values, optimized hybrid architectures can narrow the performance gap while offering sustainability advantages [3, 9, 15].

Table 4 summarizes the influence of interfacial enhancement techniques on ILSS for selected thermoplastic composite systems.

Table 4. Influence of interfacial modification and hybridization on interlaminar shear strength

Modification approach	Reinforcement system	Matrix polymer	ILSS improvement (%)	Reference
CNT addition	Glass fiber	PP	10–25	[2, 12]
Fiber hybridization	Glass/natural fiber	PP	8–18	[3, 15]
Surface sizing	Carbon fiber	PET	12–20	[6, 24]

3.3. Comparative Discussion

In general, commingled yarn architectures provide superior baseline ILSS due to enhanced filament dispersion and impregnation uniformity. However, intermingled yarn systems can achieve comparable interlaminar performance through targeted interfacial modification and optimized processing conditions. These findings highlight that ILSS is not solely determined by yarn type but results from a complex interaction between yarn architecture, fabric design, and interfacial engineering strategies. Consequently, material selection should be guided by both mechanical performance requirements and processing constraints rather than yarn architecture alone.

4. Impact and Damage Tolerance Behavior

Impact resistance and damage tolerance are key performance indicators for thermoplastic textile composites intended for structural and semi-structural applications. Compared to thermoset-based systems, thermoplastic matrices generally exhibit higher strain-to-failure and energy absorption capability, which can be further enhanced through filament-level mixing in intermingled and commingled yarn architectures.

4.1. Low- and Medium-Velocity Impact Response

Under low- and medium-velocity impact loading, the energy absorption behavior of woven thermoplastic composites is primarily governed by matrix ductility, fabric architecture, and interlaminar bonding quality. Commingled yarn-based composites typically demonstrate higher peak impact force and reduced penetration depth due to improved load redistribution and uniform matrix continuity [8, 13, 20]. The enhanced impregnation quality limits delamination initiation and promotes distributed matrix cracking. Intermingled yarn composites, on the other hand, often exhibit superior damage tolerance characterized by progressive failure mechanisms. Localized matrix-rich regions can act as energy dissipation zones, delaying catastrophic damage and increasing total absorbed energy, particularly in aramid-reinforced systems [8, 21]. This behavior is advantageous for applications requiring high impact resistance rather than maximum stiffness.

Table 5 summarizes representative impact performance metrics reported for thermoplastic composites reinforced with intermingled and commingled yarns.

Table 5. Impact performance of thermoplastic composites reinforced with intermingled and commingled yarn systems

Reinforcement type	Matrix polymer	Yarn type	Impact energy (J)	Absorbed energy (J)	Reference
Glass fiber	PP	Commingled	20–30	14–22	[13, 16]
Glass fiber	PP	Intermingled	20–30	16–25	[21, 27]
Carbon fiber	PET	Commingled	15–25	10–18	[20, 24]
Aramid fiber	PP	Intermingled	25–40	20–32	[8, 21]

4.2. Damage Mechanisms and Failure Modes

Post-impact damage analysis reveals distinct failure modes associated with yarn architecture. Commingled yarn composites tend to exhibit localized matrix cracking and limited delamination zones due to strong interfacial bonding. In contrast, intermingled yarn systems often display more diffuse damage patterns, including matrix yielding, fiber pull-out, and controlled delamination propagation [11, 18].

The woven fabric structure also plays a decisive role in damage development. Plain weave fabrics generally show higher resistance to crack propagation due to frequent yarn interlacing, while twill and satin weaves may exhibit higher absorbed energy but larger damaged areas [1, 14]. These observations underline the importance of balancing fabric architecture and yarn type when designing impact-resistant thermoplastic composite structures.

Table 6 provides a qualitative comparison of dominant damage mechanisms observed in intermingled and commingled yarn-reinforced thermoplastic composites.

Table 6. Dominant damage mechanisms in impact-loaded thermoplastic textile composites

Yarn type	Dominant damage mechanisms	Damage tolerance	Reference
Commingled	Matrix cracking, limited delamination	Moderate–high	[13, 20]
Intermingled	Matrix yielding, fiber pull-out, diffuse delamination	High	[8, 21]

4.3. Comparative Discussion

Overall, commingled yarn architectures provide improved impact stiffness and resistance to initial damage initiation, whereas intermingled yarn systems exhibit enhanced damage tolerance and higher absorbed energy under impact loading. The selection between these two yarn types should therefore be guided by the specific impact performance requirements of the intended application. For energy-absorbing structures and protective components, intermingled yarn-based thermoplastic composites appear particularly promising, while commingled systems are more suitable for applications prioritizing stiffness and dimensional stability.

5. Effect of Reinforcement Type: Synthetic, Natural and Hybrid Fibers

The type of reinforcing fiber plays a decisive role in determining the mechanical, impact, and durability-related performance of thermoplastic composites produced from intermingled and commingled yarn architectures. While synthetic fibers such as glass, carbon, and aramid dominate high-performance applications, increasing attention has been directed toward natural and hybrid fiber systems due to sustainability, weight reduction, and cost considerations.

5.1. Synthetic Fiber Reinforced Systems

Glass, carbon, and aramid fibers remain the most widely used reinforcements in intermingled and commingled thermoplastic composites. Glass fiber systems offer a balanced combination of strength, stiffness, and cost efficiency, making them attractive for semi-structural applications. Carbon fiber reinforced composites, particularly when produced using commingled yarns, exhibit superior tensile and flexural properties due to enhanced filament dispersion and high fiber modulus [1, 4, 6].

Aramid fiber reinforced thermoplastic composites demonstrate distinct behavior characterized by high impact resistance and damage tolerance rather than maximum stiffness. Intermingled yarn architectures are especially effective for aramid systems, as localized matrix-rich regions promote energy dissipation and fiber pull-out mechanisms under impact loading [8, 21].

Table 7 compares representative mechanical and impact properties of thermoplastic composites reinforced with synthetic fibers using intermingled and commingled yarns.

Table 7. Comparative properties of synthetic fiber reinforced thermoplastic composites produced from intermingled and commingled yarns

Fiber type	Matrix polymer	Yarn type	Key performance attributes	Reference
Glass	PP	Intermingled / Commingled	Balanced strength, good processability	[4, 14, 16]
Carbon	PET	Commingled	High stiffness and strength	[1, 6, 24]
Aramid	PP	Intermingled	High impact resistance, damage tolerance	[8, 21]

5.2. Natural Fiber Reinforced Thermoplastic Composites

Natural fibers such as flax, jute, hemp, and other cellulosic reinforcements have been increasingly investigated as sustainable alternatives to synthetic fibers in thermoplastic composite systems. When combined with intermingled or commingled yarn architectures, natural fiber composites benefit from improved impregnation efficiency and reduced void content compared to conventional processing routes [3, 9, 10].

However, natural fiber reinforced systems generally exhibit lower absolute mechanical properties due to fiber variability, moisture sensitivity, and limited thermal stability. Despite these limitations, optimized fabric architectures and appropriate matrix selection can yield competitive performance for non-load-critical and interior applications.

Table 8 summarizes typical performance characteristics of natural fiber reinforced thermoplastic composites produced using intermingled and commingled yarn technologies.

Table 8. Performance characteristics of natural fiber reinforced thermoplastic composites

Natural fiber type	Matrix polymer	Yarn architecture	Typical advantages	Typical limitations	Reference
Flax	PP	Intermingled	Low density, good damping	Moisture sensitivity	[9, 22]
Jute	PP	Commingled	Cost-effective, sustainable	Lower strength	[3, 15]
Hemp	PLA	Intermingled	Bio-based system	Thermal stability	[10, 23]

5.3. Hybrid Fiber Systems

Hybridization strategies combining synthetic and natural fibers or different synthetic fiber types have been widely adopted to tailor composite performance. In intermingled and commingled yarn-based thermoplastic composites, hybrid systems enable a balance between mechanical performance, impact resistance, and sustainability.

Studies on glass/natural fiber hybrid composites report improved interlaminar properties and damage tolerance compared to fully synthetic systems, while maintaining acceptable stiffness levels [3, 15]. Similarly, carbon/glass and aramid/glass hybrid configurations allow cost reduction and enhanced impact performance without severe loss of tensile properties.

Table 9 provides an overview of hybrid fiber configurations and their primary performance benefits in thermoplastic composites reinforced with intermingled and commingled yarns.

5.4. Comparative Discussion

Synthetic fiber reinforced thermoplastic composites remain indispensable for high-performance applications, particularly when maximum stiffness and strength are required. Nevertheless, natural and hybrid fiber systems reinforced through intermingled and commingled yarn architectures offer promising alternatives for applications where sustainability, impact resistance, and cost efficiency are prioritized. The selection of reinforcement type should therefore be guided by a holistic assessment of mechanical requirements, environmental considerations, and processing constraints.

Table 9. Hybrid fiber systems and their performance characteristics

Hybrid configuration	Yarn type	Primary benefit	Typical application	Reference
Glass / natural fiber	Intermingled	Improved sustainability and damping	Interior panels	[3, 15]
Carbon / glass	Commingled	Cost–performance balance	Structural panels	[6, 24]
Aramid / glass	Intermingled	Enhanced impact resistance	Protective components	[8, 21]

6. Thermoplastic versus Thermoset Matrix Comparisons

A direct comparison between thermoplastic and thermoset matrix systems is essential for assessing the true advantages of intermingled and commingled yarn-based textile composites. While the yarn architectures reviewed in Part I are primarily developed for thermoplastic processing routes, several studies have reported comparative evaluations using identical textile reinforcements combined with either thermoplastic or thermoset matrices.

6.1. Mechanical Performance Comparison

In terms of quasi-static mechanical properties, thermoset matrix composites generally exhibit higher initial stiffness due to their highly crosslinked network structure. However, thermoplastic matrix composites produced from intermingled and commingled yarns demonstrate comparable tensile and flexural strengths when impregnation quality is optimized through filament-level mixing and appropriate consolidation parameters [4, 16, 24].

One of the most notable differences lies in damage tolerance and post-yield behavior. Thermoplastic composites show higher strain-to-failure and improved resistance to crack propagation, particularly under impact and interlaminar loading. This behavior is strongly associated with the ductile nature of thermoplastic matrices and enhanced fiber–matrix adhesion achieved via commingled or intermingled architectures [8, 13, 21]. Table 10 presents a comparative overview of mechanical performance metrics for thermoplastic and thermoset matrix composites reinforced with similar woven textile architectures.

6.2. Processing, Sustainability and Lifecycle Considerations

From a processing perspective, thermoplastic composites reinforced with intermingled and commingled yarns offer significant advantages, including shorter cycle times, weldability, and the potential for reshaping and recycling. The elimination of resin infusion and curing stages simplifies manufacturing and reduces energy consumption in high-volume production scenarios [14, 17].

Table 10. Mechanical performance comparison between thermoplastic and thermoset matrix textile composites

Matrix type	Typical matrix	Tensile behavior	Impact resistance	Recyclability	Reference
Thermoplastic	PP, PET, PA	Moderate–high strength, high ductility	High	Yes	[4, 16, 21]
Thermoset	Epoxy, polyester	High stiffness, brittle failure	Moderate	No	[24, 27]

Thermoset matrix systems, although well-established in aerospace and high-performance applications, suffer from longer processing times, limited recyclability, and environmental concerns related to curing agents and waste disposal. Recent comparative studies emphasize that thermoplastic composites provide a more sustainable solution, particularly when combined with recycled or bio-based polymer matrices [22, 25]. Table 11 summarizes key processing and sustainability-related differences between thermoplastic and thermoset matrix textile composites.

Table 11. Processing and sustainability comparison of thermoplastic and thermoset matrix composites

Aspect	Thermoplastic composites	Thermoset composites	Reference
Processing cycle time	Short	Long	[14, 17]
Recyclability	High	Limited	[22, 25]
Repairability	Possible (welding)	Limited	[16, 27]

6.3. Comparative Discussion

Overall, thermoplastic matrix composites reinforced with intermingled and commingled yarns provide a compelling balance between mechanical performance, damage tolerance, and sustainability. Although thermoset composites may still be preferred for applications requiring maximum stiffness and thermal stability, the advantages offered by thermoplastic systems in terms of recyclability, impact resistance, and manufacturing efficiency make them increasingly attractive for a wide range of engineering applications. These comparative findings further reinforce the relevance of intermingled and commingled yarn technologies as enabling platforms for next-generation textile composite systems.

7. Durability, Aging and Environmental Effects

The long-term performance of thermoplastic textile composites reinforced with intermingled and commingled yarns is strongly influenced by environmental exposure conditions such as humidity, temperature fluctuations, ultraviolet radiation, and oxidative atmospheres. Durability-related properties are particularly critical for applications in automotive, construction, and outdoor structural components, where sustained mechanical integrity over the service life is required.

7.1. Moisture and Humidity Effects

Moisture uptake can significantly affect the mechanical performance of textile-reinforced composites by altering fiber–matrix interfacial adhesion and inducing matrix plasticization. Thermoplastic composites produced from intermingled and commingled yarns generally exhibit lower moisture-induced degradation compared to thermoset systems, owing to the absence of hydrolytically sensitive crosslinked networks and improved impregnation uniformity [25, 27].

Comparative studies indicate that commingled yarn-based composites demonstrate slightly better resistance to moisture-induced stiffness reduction due to their more homogeneous matrix distribution. However, intermingled yarn systems may show improved damage tolerance after conditioning, as localized matrix-rich regions can accommodate swelling stresses and delay interfacial debonding [14, 21]. Table 12 summarizes reported effects of humidity exposure on the mechanical properties of thermoplastic composites reinforced with intermingled and commingled yarns.

Table 12. Effect of humidity exposure on mechanical properties of thermoplastic textile composites

Yarn type	Matrix polymer	Exposure condition	Property change	Reference
Commingled	PP	95% RH, 500 h	Tensile modulus −5–10%	[25, 27]
Intermingled	PP	95% RH, 500 h	ILSS −8–15%	[14, 21]

7.2. Thermal and Oxidative Aging

Thermal aging and oxidative environments can lead to chain scission, matrix embrittlement, and degradation of fiber–matrix interfaces in polymeric composite systems. Thermoplastic matrices such as polypropylene and polyethylene terephthalate show varying sensitivity to elevated temperatures and oxidative agents, depending on stabilization additives and processing history.

Recent investigations have shown that intermingled and commingled thermoplastic composites exhibit improved resistance to thermal aging compared to equivalent thermoset-based systems, particularly under cyclic temperature and ozone exposure conditions [26]. The enhanced fiber wetting achieved through filament-level mixing limits oxygen diffusion pathways and reduces the rate of interfacial degradation. Table 13 presents comparative observations on thermal and oxidative aging behavior of thermoplastic textile composites.

Table 13. Thermal and oxidative aging effects in thermoplastic textile composites

Aging condition	Matrix polymer	Observed effect	Relative resistance	Reference
Thermal cycling	PP	Moderate stiffness reduction	High	[26]
Ozone exposure	PET	Minor strength loss	Very high	[26]

7.3. Comparative Discussion

Overall, thermoplastic textile composites reinforced with intermingled and commingled yarns demonstrate favorable durability and environmental resistance compared to conventional thermoset counterparts. While commingled yarn systems tend to provide slightly better resistance to moisture-induced stiffness degradation, intermingled yarn architectures offer enhanced tolerance to environmental aging through stress relaxation and damage accommodation mechanisms. These findings emphasize that durability performance is governed by a combination of yarn architecture, matrix chemistry, and environmental exposure conditions, and should be considered as a primary design criterion in long-term composite applications.

8. Comparative Summary and Design Guidelines

The comparative evaluation presented in Part II highlights that the performance of thermoplastic textile composites reinforced with intermingled and commingled yarns is governed by a complex interaction between yarn architecture, reinforcement type, matrix system, and processing conditions. Rather than identifying a universally superior yarn technology, the reviewed studies emphasize application-specific optimization strategies.

8.1. Overall Performance Comparison

A consolidated comparison of key mechanical, impact, durability, and processing-related attributes of intermingled and commingled yarn-based thermoplastic composites is provided in Table 14. This summary enables a rapid assessment of the relative advantages and limitations associated with each yarn architecture.

8.2. Application-Oriented Design Guidelines

Based on the comparative analysis, practical design guidelines can be formulated for selecting appropriate yarn architectures and material systems according to application requirements. Table 15 links typical application fields with recommended yarn type, reinforcement selection, and matrix system.

Table 14. Overall comparison of intermingled and commingled yarn-based thermoplastic composites

Performance criterion	Intermingled yarn systems	Commingled yarn systems	Design implication
Tensile stiffness	Moderate	High	Prefer commingled for stiffness-driven designs
Tensile strength	Moderate–high	High	Both suitable with optimized processing
Flexural performance	Moderate–high	High	Fabric architecture critical
Interlaminar shear strength	Moderate	High	Interface modification beneficial for intermingled
Impact energy absorption	High	Moderate–high	Intermingled favored for energy absorption
Damage tolerance	High	Moderate	Intermingled preferred for crash/impact applications
Process robustness	High	High	Both compatible with hot press molding
Recyclability	High	High	Thermoplastic advantage

Table 15. Application-oriented material selection guidelines for thermoplastic textile composites

Application area	Recommended yarn type	Preferred reinforcement	Matrix system	Key design priority
Automotive interior panels	Intermingled	Glass / natural hybrid	PP	Impact resistance, sustainability
Automotive structural parts	Commingled	Glass / carbon	PP, PET	Stiffness, dimensional stability
Protective components	Intermingled	Aramid	PP	Energy absorption
Lightweight structural panels	Commingled	Carbon	PET	High stiffness-to-weight ratio
Sustainable composite products	Intermingled	Natural fibers	PLA, bio-PP	Environmental performance

8.3. Engineering Implications

The findings summarized in this review demonstrate that intermingled yarn systems are particularly well suited for applications requiring high damage tolerance, impact resistance, and sustainability-oriented design. In contrast, commingled yarn architectures offer superior stiffness and interlaminar performance, making them more appropriate for load-bearing applications. Importantly, hybrid material strategies and interfacial modification techniques can be employed to bridge the performance gap between these two yarn technologies.

From an engineering perspective, the integration of textile design, yarn architecture selection, and processing parameter optimization remains essential for fully exploiting the potential of intermingled and commingled yarn-based thermoplastic composites. The comparative framework presented in this section provides a practical tool for material designers and engineers aiming to tailor composite performance to specific functional requirements.

9. Conclusions and Outlook

This review part has comparatively examined the performance characteristics of thermoplastic composites manufactured from intermingled and commingled yarn-based textile preforms. Based on the evaluated literature, it is evident that yarn-level hybridization plays a critical role in determining impregnation efficiency, mechanical performance, and processing stability during press molding. Commingled yarn systems consistently demonstrate improved fiber–matrix contact and reduced impregnation distances, resulting in enhanced tensile, flexural, interlaminar shear, and impact properties. In contrast, intermingled yarn structures offer greater flexibility in yarn design, compatibility with recycled and bio-based polymers, and potential advantages in cost-sensitive or sustainability-driven applications.

The comparative tables presented in this part highlight that the performance gap between intermingled and commingled systems strongly depends on fiber type, thermoplastic matrix viscosity, fabric architecture, and molding parameters. Moreover, both systems exhibit clear advantages over conventional film-stacking approaches in terms of cycle time reduction and material efficiency. Despite their proven potential, challenges remain regarding process optimization, defect control, and large-scale industrial standardization.

Overall, intermingled and commingled yarn-based composites represent mature yet evolving material systems for press-molded thermoplastic applications. Future research should focus on hybrid yarn optimization, multi-scale modeling of impregnation behavior, and durability-driven performance evaluation to further expand their use in structural and semi-structural composite components.

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