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Development Trends in Prepreg Technologies for UAV Manufacturing under Geopolitical and Export Control Constraints (2021–2024)

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Abstract

Pre-impregnated composite materials are strategic enabling inputs for contemporary UAV manufacturing. This paper evaluates prepreg technology trends and export-control implications between 2021 and 2024, using documentary analysis of industrial disclosures, EU dual-use reports, Wassenaar control lists and Czech export-control documentation. The findings show a coupled technological-regulatory trajectory: thermoset and thermoplastic prepregs, OOA processing and AFP/ATL automation advanced alongside stricter compliance governance under Regulation (EU) 2021/821.

KEY WORDS: *composite prepregs; dual-use goods; unmanned aerial vehicle; export control; Wassenaar Arrangement; Regulation (EU) 2021/821*

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1. Introduction

Pre-impregnated composite materials (prepregs) have become a strategically significant class of aerospace materials because they combine controlled reinforcement architecture, reproducible fiber-matrix ratios and stable curing behavior. In unmanned aerial vehicle (UAV) manufacturing, these properties are directly connected with endurance, payload efficiency, structural reliability and production repeatability. The relevance of prepreg technologies is not limited to materials engineering. Since advanced carbon-fiber composites, high-performance resin systems, automated composite-processing equipment and related technical know-how may be used in both civil and military aerospace applications, prepreg supply chains are increasingly embedded in export-control governance and broader economic-security policy [1-6].

The period from 2021 to 2024 is analytically important for three reasons. First, aerospace supply chains were recovering from the disruption of the COVID-19 period while defense demand and UAV-related applications expanded in a deteriorating geopolitical environment. Second, Regulation (EU) 2021/821 established a modernized Union regime for the control of exports, brokering, technical assistance, transit and transfer of dual-use items. Third, multilateral alignment through the Wassenaar Arrangement and annual updates of EU control lists strengthened the institutional context in which manufacturers, research organizations and exporters assess advanced composite materials, production equipment and intangible technology transfer.

The central research problem of this paper is the interaction between material innovation and regulatory constraint. UAV producers require lighter, tougher and more reproducible structures, while authorities require traceability, classification discipline and licensing control over items that may contribute to military capability. This interaction is not incidental. It shapes R&D priorities, supplier selection, contractual terms, documentation practices and the geography of cross-border cooperation. For high-performance prepregs, the decisive question is not merely whether a material is technically suitable for a UAV structure, but whether its properties, production route, end use and destination create export-control obligations [7-10].

The aim of the paper is to evaluate development trends in prepreg technologies for UAV manufacturing under geopolitical and export-control constraints between 2021 and 2024. The study focuses on thermoset epoxy prepregs, thermoplastic prepregs, out-of-autoclave (OOA) processing, automated fiber placement (AFP), automated tape laying

(ATL), industrial supply-chain capacity and dual-use governance. The paper contributes to the security and defense studies literature by linking aerospace composite engineering with export-control compliance and supply-chain resilience. Its added value lies in treating prepreg technology as a socio-technical capability, rather than as a purely material input.

2. Conceptual and Regulatory Background

Prepregs are semi-finished composite materials in which fibers are pre-impregnated with a controlled amount of resin. Carbon-fiber prepregs are especially relevant for UAV airframes because they offer high specific strength and stiffness, low weight, dimensional stability and predictable laminate performance. In comparison with wet lay-up or less controlled infusion routes, prepregs support higher process repeatability and tighter quality assurance. These attributes are critical in wings, fuselage shells, control surfaces, bulkheads, sandwich panels and internal load-bearing structures where mass reduction and structural reliability determine operational performance [5].

From a technological perspective, the UAV sector uses both thermoset and thermoplastic prepreg systems. Thermoset epoxy prepregs remain dominant in many aerospace structures because their processing, qualification and long-term durability are well established. Toughened epoxy systems improve damage tolerance, fracture toughness and environmental resistance, which is important for UAV platforms exposed to vibration, thermal cycling and operational wear. Thermoplastic prepregs, including systems based on PEEK, PEKK and PPS families, provide weldability, impact resistance, storage advantages and potential recyclability. They are attractive for modular UAV architectures and faster manufacturing environments, even though their broader adoption depends on processing temperature, tooling, joining methods and certification maturity [5, 6].

The industrial development of prepreg technologies is closely linked to manufacturing processes. OOA curing reduces dependence on autoclave capacity and can support medium-scale or decentralized production. AFP and ATL enable automated deposition of tapes or tows according to digitally defined fiber paths. These processes improve fiber orientation, reduce waste, increase repeatability and support digital traceability. In UAV manufacturing, where production volumes may range from prototypes to serial defence-related platforms, the combination of prepreg materials and automated processing creates both operational advantages and regulatory sensitivity [5, 6].

The regulatory background is defined by the EU dual-use framework and the multilateral control regimes on which EU lists are based. Regulation (EU) 2021/821 sets up the Union regime for the control of exports, brokering, technical assistance, transit and transfer of dual-use items. Its scope includes physical goods, software and technology. Annex I contains the list of controlled dual-use items, while Annex IV identifies particularly sensitive items subject to additional intra-Union transfer controls. The Wassenaar Arrangement provides the principal multilateral reference for many dual-use goods and technologies relevant to conventional arms and sensitive advanced technologies. In practice, this means that aerospace-grade fibers, prepregs, composite structures, production equipment, software and development or production technology may require careful classification against control-list parameters [7-10].

The dual-use character of UAV-related composite technology is intensified by the operational ambiguity of UAV platforms. Civilian UAVs support infrastructure inspection, mapping, agriculture, border monitoring, disaster response and environmental surveillance. Similar airframe technologies may also support military reconnaissance, loitering systems, target acquisition, electronic warfare or strike platforms. The same lightweight composite wing skin or fuselage shell may therefore be embedded in very different end-use contexts. Export-control governance responds to this ambiguity by combining technical parameters, end-use assessment, destination risk, sanctions screening and licensing procedures [7-10].

Geopolitical developments after 2021 increased the strategic significance of this governance environment. Russia's aggression against Ukraine, the growth of drone warfare, concerns about technology leakage and the securitisation of supply chains have reinforced the importance of advanced materials in defence-industrial policy. Composite prepregs are not always the most visible component of UAV capability, yet they are a foundational enabling input. Control over materials, processing know-how and high-precision production equipment can therefore influence the pace, quality and autonomy of UAV production [7-10].

3. Materials and Methods

The research applies longitudinal documentary analysis covering four consecutive reporting years, 2021-2024. The method was selected because much of the relevant information on advanced composite materials, UAV manufacturing and export-control decisions is dispersed across corporate annual reports, technical releases, EU implementation documents, national export-control reports and control-list publications. A documentary approach allows the study to correlate technological development with institutional governance without relying on confidential industrial data.

The source base consists of four categories. The first category includes industrial disclosures by major aerospace composite manufacturers and technology suppliers, especially annual reports and technical releases describing carbon-fiber prepregs, thermoplastic composites, aerospace demand, automation, sustainability and defence-related market dynamics. The second category includes EU legal and policy documents, with Regulation (EU) 2021/821 serving as the core legal framework. The third category includes multilateral control-list documentation of the Wassenaar Arrangement. The fourth category includes national export-control reporting, with particular attention to Czech Ministry of Industry and Trade documentation and the role of customs authorities in the supervision of dual-use exports [11-15].

The analytical procedure consisted of three steps. First, key technological trends were extracted and coded into thematic categories: thermoset prepregs, thermoplastic prepregs, OOA processing, AFP/ATL automation, digital quality assurance and supply-chain resilience. Second, export-control and compliance-related requirements were coded into categories: classification, licensing, end-use assessment, intangible technology transfer, documentation, internal compliance programs and transparency reporting. Third, the two coding layers were compared across the 2021-2024 period in order to identify points of convergence between technological evolution and regulatory pressure.

The study does not attempt to calculate a complete market size for UAV prepregs. Such a calculation would require proprietary production data, platform-level bill-of-material information and classified procurement figures. Instead, the paper provides a structured qualitative synthesis of publicly available evidence.

The research has three limitations. First, the most sensitive data on defence UAV supply chains, export denials and classified end users are not publicly available. Second, companies often report composite activities at the level of broad aerospace or industrial segments rather than as UAV-specific prepreg production. Third, dual-use classification depends on precise technical parameters and end-use context; therefore, public documents rarely permit definitive item-by-item classification. These limitations are addressed by avoiding unsupported quantitative claims and by focusing on documented trends, regulatory architecture and analytically defensible relationships.

4. Results

The investigation indicates that prepreg technologies followed a coupled technological-regulatory trajectory between 2021 and 2024. Material innovation and process automation advanced in parallel with strengthened export-control governance. The result was not a simple conflict between industry and regulation, but a structural integration of compliance into aerospace composite manufacturing. The most important trends are summarised in Table 1.

Table 1.

Main technological and regulatory trends in UAV prepreg manufacturing, 2021-2024

Trend	Technological relevance	UAV manufacturing implication	Export-control implication
Toughened epoxy prepregs	Improved fracture toughness, fatigue behaviour and environmental resistance.	Reliable primary structures, wing skins, fuselage shells and control surfaces.	Classification depends on material parameters, destination and end-use context.
Thermoplastic prepregs	Weldability, impact resistance, storage advantages and recyclability potential.	Modular UAV structures, repairable components and faster production concepts.	Potential sensitivity when combined with aerospace-grade fibers and controlled technology.
OOA processing	Composite curing without full autoclave dependence.	Medium-scale and decentralised UAV production with lower infrastructure barriers.	Diffusion of production capability increases need for technology-transfer control.
AFP/ATL automation	Precise fiber orientation, lower scrap, repeatable lay-up and digital process control.	Serial production, quality assurance and structural reproducibility.	Production equipment, software and know-how may require control-list assessment.
Compliance integration	Traceability, documentation and internal control systems integrated into production.	Greater reliability for international aerospace supply chains.	Licensing, end-use checks and intangible technology-transfer management become strategic.

Thermoset epoxy prepregs remained the dominant material family for primary UAV structural components. Their advantages include established aerospace qualification pathways, high fatigue performance, predictable cure cycles and strong compatibility with existing tooling and inspection regimes. Between 2021 and 2024, industrial reporting emphasised toughened resin systems, improved environmental resistance and process optimisation. These developments support UAV components requiring dimensional stability and resistance to mechanical loading, including wing skins, fuselage shells, control surfaces and internal frames.

Thermoplastic prepregs gained strategic relevance but did not replace thermoset systems. Their principal advantages are weldability, impact resistance, faster consolidation potential and recyclability. For UAV manufacturing, thermoplastic composites can support modular structures, repairable components and higher-rate production concepts. Their constraints include higher processing temperatures, equipment requirements and qualification complexity. The observed trend is therefore complementary integration rather than wholesale substitution. Thermoset systems remain structurally dominant in many certified or high-performance applications, while thermoplastics represent a growing pathway for flexible production and sustainability-oriented design.

OOA prepreg processing matured as a route for high-quality composite fabrication without complete dependence on autoclave infrastructure. For the UAV sector, this is significant because autoclaves are capital-intensive and may constrain production scalability. OOA processing can enable distributed production, smaller manufacturing cells and reduced energy intensity, provided that void content, consolidation quality and cure control remain within acceptable limits. In security terms, decentralised OOA capability may also complicate export-control monitoring because advanced manufacturing competence can diffuse beyond traditional aerospace prime contractors.

AFP and ATL technologies strengthened the link between prepreg materials and digital manufacturing. Automated placement improves ply accuracy, fiber orientation control, waste reduction and traceable process documentation.

This is particularly relevant for serial UAV production where repeatability and cost discipline are decisive. Digital traceability also has a compliance function. It enables manufacturers to document material batches, processing parameters, component histories and quality-assurance records. The same data infrastructure that supports engineering quality can support export-control due diligence and contractual compliance.

Supply-chain resilience became a persistent theme during the observed period. Advanced composite manufacturing depends on carbon-fiber precursors, resin chemistry, prepregging capacity, freezer logistics, tooling, inspection, skilled labour and certification knowledge. Geopolitical shocks, sanctions regimes and defence demand growth increased pressure on companies to diversify suppliers and secure critical inputs. UAV programmes are especially sensitive because they may combine rapid development cycles with controlled components and export restrictions. As a result, supply-chain governance increasingly includes not only cost and delivery considerations, but also jurisdictional risk, licensing reliability and traceability.

The Czech industrial position is characterised by downstream competence rather than large-scale primary carbon-fiber prepreg production. Companies such as Havel Composites CZ, 5M and AERO Vodochody Aerospace demonstrate capabilities in composite processing, structural panels, sandwich structures, aerospace assemblies and autoclave-based production. This positions Czech industry within the high-value integration segment of the composite supply chain. The strategic relevance of this position should not be underestimated. Even where primary prepreg manufacture is limited, downstream processing competence can support UAV structural manufacturing, prototyping, repair, testing and integration [15, 16, 17].

The export-control results show that Regulation (EU) 2021/821 and Wassenaar-based list updates created a governance environment in which advanced composite technologies must be assessed not only by product description but also by technical parameters, software, know-how and end use. For manufacturers, the practical implication is the need for systematic classification workflows. Materials, semi-finished prepregs, composite structures, production equipment and technical assistance may fall into different control categories depending on their properties and application. The risk is particularly high when UAV-related projects involve non-EU partners, defence customers, sensitive destinations or transfers of manufacturing know-how [8].

Compliance management therefore became a structural part of competitiveness. Firms able to classify products, maintain internal compliance programmes, document end-use checks and manage licensing timelines are better positioned to participate in international aerospace supply chains. Conversely, weak compliance capacity may delay exports, restrict research cooperation or expose organisations to legal and reputational risk. This is especially relevant for universities and research organisations involved in UAV composite R&D, because intangible technology transfer can occur through data sharing, joint design work, laboratory access, training or publication of sensitive process parameters.

A further result concerns the time asymmetry between technological innovation and regulatory adaptation. Composite materials and manufacturing methods evolve rapidly, while control-list updates and administrative interpretations often move more slowly. This creates uncertainty for manufacturers introducing new resin systems, hybrid laminates, nano-modified matrices or automated production routes. The uncertainty is not merely legal; it affects investment decisions, customer commitments and market-entry strategies. Where classification is ambiguous, exporters may adopt conservative licensing practices or redesign supply-chain arrangements to reduce regulatory exposure.

5. Discussion

The findings demonstrate that prepreg technologies for UAV manufacturing should be understood as part of a socio-technical security system. The technical performance of a material cannot be separated from the governance structures that condition its movement across borders. Carbon-fiber prepregs, thermoplastic matrices, AFP equipment and process know-how acquire strategic significance because they contribute to the quality and scalability of UAV airframes. Export-control regimes respond by transforming material properties and manufacturing capabilities into objects of legal classification and institutional oversight. This socio-technical interpretation helps explain why incremental technological improvements can have strategic consequences. Improved fracture toughness, reduced porosity or more reproducible fiber placement may appear as narrow engineering achievements. In the UAV context, however, they can increase endurance, payload ratio, survivability and operational reliability. When multiplied across serial production, these improvements may influence defence capability. The regulatory system therefore treats advanced composites not only as commercial goods, but as potential force-enabling technologies.

The relationship between innovation and regulation is ambivalent. On the one hand, export controls may slow collaboration, increase administrative costs and create uncertainty for companies operating in global supply chains. On the other hand, credible compliance can protect sensitive technology, preserve market access and enhance trust between firms, governments and research partners. For aerospace composite manufacturers, compliance is no longer a peripheral legal function. It is an element of industrial strategy, risk management and corporate governance.

The analysis also shows that the dual-use problem is not solved by distinguishing civil and military UAVs at a superficial level. Many composite technologies are platform-agnostic. A prepreg used in a civil inspection drone may share material characteristics with structures used in defence applications. Similarly, automated placement knowledge or cure-cycle optimisation can be transferable across programmes. Effective governance must therefore integrate technical classification with end-use analysis and destination risk. Overly formal product descriptions are insufficient if they fail to capture the practical capability enabled by the technology.

For research organisations, the implications are substantial. Academic projects involving UAV structures, carbon-fiber laminates, thermoplastic consolidation, automated lay-up or structural optimisation should include export-control screening at the project-design stage. This does not mean that academic research should be restricted by default. It means that research governance must identify controlled parameters, sensitive partners, data-transfer pathways and publication risks. The same principle applies to doctoral projects, laboratory demonstrations and industry-sponsored research where technical know-how may be transferred to external entities.

For policymakers, the main challenge is to maintain proportionality. Excessively slow or ambiguous classification processes may weaken European competitiveness and delay innovation. Insufficient control may enable the diffusion of sensitive technology to actors whose end uses conflict with European security interests. A balanced approach requires better technical expertise within licensing authorities, clearer guidance for emerging composite technologies and more predictable communication with industry. The Czech case illustrates the importance of connecting national industrial capabilities with EU-level governance and customs practice. The period 2021-2024 also suggests that supply-chain resilience and export control are converging policy agendas. Traditional resilience focuses on continuity of supply, redundancy, logistics and cost. In controlled advanced-technology sectors, resilience additionally requires licensing predictability, documentation discipline, trusted partners and the ability to substitute suppliers without violating control obligations. UAV prepreg supply chains are therefore not only engineering systems; they are regulated networks whose stability depends on both material availability and institutional reliability.

The discussion further indicates that European industry should not assess competitiveness only through production capacity. In advanced composite manufacturing, competitiveness includes the ability to integrate materials engineering, automated processing, quality assurance, digital traceability and compliance governance. This integrated capability is especially valuable for small and medium-sized firms that operate as specialised suppliers within larger aerospace networks. If such firms can demonstrate robust compliance and technical quality, they may strengthen their position even without controlling upstream carbon-fiber or prepreg production.

A final interpretive point concerns transparency. Public reporting on dual-use exports has improved, but data remain fragmented and often insufficient for sector-specific analysis. Reports frequently aggregate categories in ways that do not reveal the role of composite materials or UAV-related technologies. This limits the ability of researchers to evaluate how export controls affect innovation and trade in specific sectors. More granular but security-conscious reporting would support evidence-based policy without necessarily disclosing sensitive commercial or operational details [8, 9, 11-14].

Limitations and further research. The principal limitation of this study is the restricted availability of detailed data. Due to the sensitivity of UAV manufacturing, export licensing and controlled technologies, many relevant datasets are classified, commercially confidential or aggregated at a level that prevents precise sectoral attribution. State actors and private companies are often reluctant to disclose hard data on controlled materials, customers, denied licences or dual-use classification disputes.

A second limitation is the pace mismatch between technological development and administrative interpretation. New resin systems, hybrid laminates and automated processing routes may enter commercial use before customs authorities and licensing bodies provide detailed interpretive guidance. This can create compliance uncertainty and inconsistent decision-making. Further research should therefore examine how exporters manage classification ambiguity, how long licensing procedures take in practice and whether divergent national interpretations affect industrial competitiveness within the EU single market.

Further research should also improve the empirical mapping of advanced composite material flows. A combination of customs data, corporate reporting, patent analysis and expert interviews could provide a more detailed picture of European capabilities in carbon-fiber prepregs and UAV structures. Such research would help policymakers align export-control governance with technological reality while supporting legitimate innovation in the European aerospace sector.

6. Conclusions

The paper evaluated development trends in prepreg technologies for UAV manufacturing under geopolitical and export-control constraints between 2021 and 2024. The analysis confirms that thermoset carbon-fiber prepregs remained structurally dominant in UAV-relevant aerospace components, while thermoplastic prepregs gained importance as complementary materials associated with weldability, impact resistance, production flexibility and sustainability. OOA processing, AFP and ATL automation strengthened the industrial relevance of prepregs by improving repeatability, laminate precision, waste reduction and digital traceability.

The regulatory analysis shows that these technological developments occurred within a strengthened dual-use governance environment. Regulation (EU) 2021/821, Wassenaar-based control-list alignment and national export-control reporting increased the importance of classification, licensing, end-use assessment and internal compliance programmes. The interaction between technology and regulation is therefore not external to UAV prepreg manufacturing; it is a defining condition of market access, research cooperation and supply-chain design.

The main contribution of the article is the identification of a coupled technological-regulatory trajectory. Material innovation and process automation expanded the performance potential of UAV structures, while export-control governance shaped how these technologies could be transferred, commercialised and integrated across borders. For industry, the practical implication is the need to treat compliance as part of engineering and supply-chain strategy. For research organisations, the implication is the need to screen UAV composite projects for controlled technology and intangible transfer risks. For policymakers, the implication is the need for clearer, faster and technically informed guidance on emerging composite materials and automated manufacturing processes.

Further research should focus on three areas. First, more detailed mapping of European UAV composite supply chains is needed, including the position of SMEs and downstream processors. Second, empirical analysis of licensing delays and classification uncertainty would improve understanding of regulatory effects on innovation cycles. Third, comparative research across EU Member States could identify whether interpretive differences among licensing and customs authorities create competitive distortions. These research directions would support a more predictable regulatory environment aligned with the pace of technological development.

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