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Article

Systematic Framework for Rapid Assessment of Emerging Technological Contamination: Bilateral Quantification of Fiber Optic Drone Cable Deployment in Ukraine-Russia War

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Abstract

Fiber optic drone operations in Ukraine represent an emerging technological contamination requiring systematic assessment. This study presents the first bilateral quantification framework for per- and polyfluoroalkyl substances (PFAS) contamination from fiber optic drone cable deployment, incorporating production data from both Ukrainian and Russian forces. Based on documented 2024-2025 deployment, we calculate bilateral material accumulation of 13,080 tonnes ($\pm 35\%$ uncertainty) containing 523 tonnes of PFAS-bearing fluoropolymers distributed across approximately 50,000 km² operational areas. Ukrainian operations contributed 3,480 tonnes while Russian operations accounted for 9,600 tonnes based on Prince Vandal production exceeding 50,000 units monthly. Production-based estimates align with independent field assessments suggesting 4,176 tonnes, with the 3.1 \times difference primarily reflecting bilateral inclusion versus single-side field observations. Cable composition analysis confirms poly(methyl methacrylate) cores with fluoropolymer cladding exhibiting multi-century persistence timescales. Environmental degradation modeling projects potential annual microplastic generation of 130 tonnes ($\pm 50\%$ uncertainty) through photo-oxidative and mechanical fragmentation. Field validation confirms wildlife impacts including documented avian entanglement and livestock cable ingestion. The assessment framework addresses methodological challenges specific to distributed technological contamination where traditional point-source protocols prove inadequate. Post-war bilateral field verification remains essential for validating production-based estimates and quantifying geographic distribution heterogeneity across former combat zones.

Keywords: fiber optic drones; PFAS contamination; distributed pollution; military environmental impact; emerging contaminants; rapid assessment framework

1. Introduction

1.1. Military Technology and Environmental Challenges

Military technology deployment has historically created environmental challenges requiring scientific assessment (Certini et al., 2013; Hupy, 2008). Contemporary fiber optic-controlled drone systems present a novel pollution source that emerged rapidly with limited scientific attention, representing a knowledge gap in environmental contamination research.

Global technology proliferation accelerated during 2025, extending fiber optic drone deployment beyond the Ukraine-Russia conflict. Documented operational use includes the Azawad Liberation Front (FLA) in Mali deploying fiber optic drones against Russian African Corps forces,

and Kachin Independence Army (KIA) in Myanmar using fiber optic drone to down a Mi-17 helicopter (Lowy Institute, 2025). The FBI announced interest in acquiring fiber optic drones for law enforcement applications in the United States (DroneDJ, 2025a,b), indicating adoption by non-military agencies. The global tethered drone market, which includes fiber optic systems, expanded from \$399 million (2025) to projected \$706 million by 2034, reflecting rapid commercial and defense sector integration (Fortunebusinessinsight, 2025). This global proliferation demonstrates that distributed fiber optic contamination represents an emerging worldwide challenge (Morales et al., 2025; Hupy, 2008), not a conflict-specific phenomenon, making systematic assessment frameworks immediately applicable across multiple operational theaters (Ward et al., 2019).

Contemporary military operations employing unmanned systems present novel environmental challenges requiring systematic assessment frameworks not yet established in environmental management protocols.

1.2. Fiber Optic Drone Technology and Cable Deployment

Fiber optic-controlled drones represent a distinct unmanned aerial vehicle technology whereby aircraft maintain communication with operators through physical fiber optic cables rather than radio frequency signals. During flight, these systems unspool lightweight fiber optic cables from an onboard reel, maintaining continuous data transmission through the cable while the aircraft travels distances now extending to 30-41 kilometers from the launch point (Defense Express, 2025; RFE/RL, 2025).

This technology provides immunity to electronic warfare jamming, a critical advantage in contested electromagnetic environments (Anadolu Agency, 2025; Lowy Institute, 2025). However, the physical cable deployment mechanism creates environmental consequences not present in traditional radio-controlled systems. Once deployed, these thin cables (typically 0.1-0.25 mm diameter) remain on the terrain surface and are effectively irretrievable. Field reports confirm "long trails of fiber optic cable left behind the drones on the battlefield" creating contamination so extensive that "it's difficult, if not impossible, to trace them back to an active drone base" (CEOBS, 2025; Euromaidan Press, 2025).

The material composition of these cables reflects demanding operational requirements: optical fiber cores for signal transmission, protective cladding layers for durability, and lightweight construction for extended range.

1.3. 2025 Technology Acceleration and Bilateral Production Expansion

Technology adoption and production capacity accelerated dramatically during 2025 for both Ukrainian and Russian forces. Ukraine developed over 20 new certified fiber optic drone models with production capacity reaching 4 million drones annually by November 2025, expanding from only 10 manufacturers in 2022 to 500 manufacturers by 2025 (Bloomberg, 2025; Euromaidan Press, 2025). This represents more than double the initial 2.5 million projections and exceeds the combined annual production of all NATO countries. Ukrainian first-person view (FPV) drone output jumped from approximately 20,000 units per month in 2024 to 200,000 per month in 2025 (TS2.tech, 2025).

Russian fiber optic drone production underwent parallel acceleration. The Prince Vandal model alone reached production of over 50,000 units monthly by September 2025, representing a tenfold increase during 2025 (TASS, 2025a), though total Russian fiber optic drone production across all models remains undisclosed. Production facilities were established in three regions across Russia, with more than one facility in each region. Russian operations require approximately 6 million kilometers of fiber annually (NPR, 2025). The Prince Vandal achieves 95% hit accuracy compared to 20% for standard FPV drones, with documented statistics showing 18,900 confirmed launches destroying equipment worth \$1.7 billion (TASS, 2025b).

The establishment of specialized units like Rubicon reflects Russia's systematic approach to fiber optic technology deployment. This strategic emphasis on mass production, training infrastructure, and proven operational models suggests sustained commitment beyond temporary tactical adoption.

Such investment validates the necessity of bilateral contamination assessment and indicates continued high-volume deployment trajectories.

Operational ranges extended from initial 10-12 km deployments in 2024 (Defense Express, 2025; Lowy Institute, 2025; The Defender, 2025) to systems capable of 30-41 km by mid-2025, with some reaching 50+ km by November 2025. Low-altitude optimization and repeater systems further extended mission capabilities.

Field assessments suggest contamination density may reach 2,900 km of cable per kilometer of front line (CEOBS, 2025; NPR, 2025). However, when bilateral production data is incorporated, total contamination substantially exceeds field-based observations of geographically limited scope, emphasizing the urgent need for systematic post-war bilateral verification and empirical assessment.

Visual field evidence from December 2025 confirms extreme cable density in some operational areas. Soldiers and journalists report fields in Donbas 'covered with a web of fiber optic threads, with cables 'glinting with frost in winter' as the only visual warning (The Gateway Pundit, 2025). Vehicle entanglement in accumulated fiber optic wires has been documented, and soldiers report difficulty distinguishing cables from potential booby traps, forcing operational delays to call explosive ordnance disposal teams. Some supply routes required installation of kilometers-long protective netting 'tunnels' above roads to prevent drone strikes, while the Russian city of Belgorod covered buildings in anti-drone netting (The War Zone, 2025b). This visual evidence validates the distributed contamination paradigm and demonstrates cable accumulation exceeds baseline estimates in high-intensity operational sectors.

China's dominance in global fiber optic cable manufacturing represents a critical supply chain dimension affecting contamination scale. China leads global fiber optic cable production and supplies components to both Russian and Ukrainian drone manufacturers (Lowy Institute, November 2025; GL Fiber marketing materials, 2025). Russia benefits from close relationship with China for drone components, while Ukrainian manufacturers faced potential supply restrictions with multiple reports of China considering bans on supplying drone components to Ukraine (Defense Express, 2025; TS2.tech, 2025). Chinese companies openly market fiber optic cables for FPV drone applications, with manufacturers like GL Fiber advertising specialized drone optical fiber products (GL Fiber, 2025). The global fiber optic cable market, dominated by Chinese production, enables mass manufacturing on both sides of the conflict. This supply chain geopolitics affects contamination scale projections, as component availability determines production capacity limits. As fiber optic drone technology proliferates globally (documented use in Mali, Myanmar; FBI acquisition interest in USA), Chinese manufacturing capacity will continue influencing worldwide contamination patterns.

1.4. Scale of Contemporary Deployment

Recent military operations have accelerated fiber optic drone deployment to unprecedented levels. Ukraine's documented production reached "at least 1 million drones" in 2024, expanding to 4 million drones annually by November 2025 (Bloomberg, 2025; Pravda, 2025; Ukrainska Pravda, 2025). This represents production capacity exceeding all NATO countries combined, with Ukraine operating approximately 500 domestic manufacturers by 2025, up from only 10 manufacturers in 2022 (Bloomberg, 2025; TS2.tech, 2025). Field-verified fiber optic usage ranges from 6-10% of total deployment (The War Zone, 2025; CEOBS, 2025), demonstrating the emerging scale of this contamination challenge.

Evidence confirms that both Ukrainian and Russian forces extensively employ this technology (Washington Post, 2025; TASS, 2025a,b), though detailed bilateral field verification awaits post-war access conditions.

1.5. Environmental Persistence and PFAS Concerns

Unlike conventional military waste with established disposal protocols, distributed fiber optic contamination requires novel assessment approaches currently absent from environmental management frameworks (Lawrence et al., 2015; Supplementary Material S10.3). These cables contain

persistent of per- and polyfluoroalkyl substances (PFAS) compounds in their fluoropolymer cladding that "do not readily degrade in the environment and can contaminate soil and water" (CEOBS, 2025).

Environmental persistence projections indicate polymethyl methacrylate (PMMA) degradation timescales of 400-1,200 years, while fluoropolymers persist on geologic timescales (Chamas et al., 2020; detailed assessment in Section 2.5). High molecular weight fluoropolymers exhibit extreme environmental persistence but limited bioavailability due to their polymeric structure (Henry et al., 2018). However, long-term environmental degradation may gradually release low molecular weight PFAS compounds including processing aids and residual monomers that do demonstrate bioaccumulation potential and environmental mobility (Wang et al., 2017). These extended persistence timescales enable progressive fragmentation processes.

Environmental plastic degradation leads to microplastic formation through UV radiation, thermal stress, and mechanical fragmentation, with formation rates varying by polymer type and environmental conditions (Zhang et al., 2021).

1.6. Research Gap and Study Objectives

Current research on technological waste from military operations reveals substantial gaps in understanding, with electronic waste contributing 12-18% of global pollution through polymer degradation pathways (Ziani et al., 2023). Military-grade materials exhibit enhanced environmental persistence due to specialized additive packages, presenting contamination challenges distinct from civilian plastic pollution (Henry et al., 2018; Hupy, 2008).

This study addresses urgent research needs through systematic framework development that can guide immediate research priorities while providing transferable methodology for similar emerging contamination challenges globally. The framework incorporates established methodologies for assessing polymer environmental persistence while addressing the unique characteristics of distributed military technology waste requiring immediate scientific attention. Our assessment focuses on documented Ukrainian deployment patterns due to production data availability, while acknowledging that bilateral assessment requires post-war field verification.

Military waste management in deployed settings presents substantial challenges, with nonhazardous waste generation rates reaching 4-21.5 pounds per capita daily (Morales et al., 2025; Supplementary Material S10). The U.S. Department of Defense (2025) has completed preliminary assessments at 703 installations for PFAS contamination as of March 2025, with 586 sites now proceeding to remedial investigation. While these protocols effectively address point-source contamination at fixed installations, they provide no established framework for assessing distributed technological waste from active operations.

2. Materials and Methods

2.1. Regulatory Context

The U.S. Environmental Protection Agency established Maximum Contaminant Levels (MCLs) of 4 ng/L for perfluorooctanoic acid (PFOA) and perfluorooctane sulphonate (PFOS) in 2024, with corresponding Maximum Contaminant Level Goals set at zero given persistent health concerns (U.S. EPA, 2024). Concurrently, European fluoropolymer manufacturers achieved voluntary emissions reductions below 0.009% to air and 0.001% to water by the end of 2024, targeting further reductions to 0.003% and 0.0006% respectively by 2030 (Fluoropolymers Group, 2025). The scope of PFAS contamination continues expanding rapidly, with detection at 7,457 sites across all U.S. states as of August 2024—a 20% increase from 6,189 sites documented just three months earlier (Environmental Working Group, 2024).

These regulatory developments have direct implications for post-war cable remediation, where processing technologies will need to achieve >99.9% PFAS removal efficiency to meet emerging standards. Cost estimates and technology selection criteria must account for this evolving regulatory landscape, as treatment facilities face progressively stricter compliance requirements. Importantly,

European manufacturing programs demonstrate that substantial emissions reductions are technically achievable within current industrial frameworks, establishing precedent for contamination control standards in remediation contexts. The rapid pace of contaminated site identification—a 20% increase in just three months—underscores both the scale of PFAS contamination challenges and the critical need for systematic assessment frameworks capable of rapid deployment in emerging scenarios.

2.2. Framework Development Approach

We developed an interdisciplinary assessment framework specifically designed for emerging technological contamination where traditional empirical approaches face significant access constraints (Suter, 2007). The methodology emphasizes systematic uncertainty quantification, transparent limitation acknowledgment, and structured validation pathways rather than definitive quantitative conclusions (Linkov & Ramadan, 2004). The framework integrates established protocols for polymer degradation assessment (Chamas et al., 2020) with novel approaches for distributed military technology waste evaluation.

2.3. Data Sources

We conducted targeted web searches on June 9, 2025, focusing on publicly available military technology assessments, with systematic monthly updates through November 2025 to incorporate emerging production data and field observations, focusing on publicly available military technology assessments, environmental impact evaluations, and verified production statistics. While this rapid assessment approach enabled timely framework development, we acknowledge that systematic review with formal search protocols would strengthen future validation. The current methodology prioritizes rapid response to an emerging contamination challenge over exhaustive literature synthesis. Complete data sources and validation protocols are provided in Supplementary Material S1.1.

Key data sources include:

- Ukrainian drone production: Bloomberg (2025), Ukrainska Pravda (2025), DroneLife (2025) for 2025 capacity; Bloomberg (2025) investigative reporting for 2024
- Russian drone production: TASS (2025b) official reporting on Prince Vandal production capacity
- 2025 technology acceleration: Defense Express (2025), The Defender (2025), TS2.tech (2025)
- Fiber optic deployment rates: The War Zone (2025a), TS2.tech (2025) field assessments, CEOBS (2025) 10% estimate
- Field-based density validation: CEOBS (2025), NPR (2025) assessments including doug weir interview
- Environmental impact evidence: CEOBS (2025), Technology.org (2025), British Ornithologists' Union (2025), Fast Company (August 2025)
- Material composition: Industrial Fiber Optics Inc (2024) and CEOBS (2025)
- Regulatory updates: European Chemicals Agency (ECHA) (2025), Akin Gump (2025), Linklaters (2025)

2.3.1. Russian-Sourced Data: Verification Framework and Limitations

Bilateral contamination assessment requires incorporation of Russian military production data, presenting methodological challenges given Ukrainian legal restrictions on citing Russian sources, potential for data falsification in state media, and absence of independent verification during active conflict.

We address these challenges through systematic verification incorporating multiple independent corroboration sources. Russian production claims (TASS reports of 50,000+ Prince Vandal drones monthly, 2025b) are corroborated by independent expert assessment (NPR/CEOBS, 2025: ~6 million km fiber annually = 7,200 tonnes, matching our production-based calculations),

Washington Post reporting (2025) confirming deployment acceleration, Ukrainian military field observations, and recovered system documentation.

We apply conservative bias assessment recognizing that production capacity claims for deployed weapons differ from battlefield effectiveness claims, with verification possible through component imports, facility observations, and captured equipment analysis. All Russian production figures are treated as requiring post-war independent verification, with uncertainty ranges ($\pm 20\%$) exceeding Ukrainian estimates ($\pm 10\%$) to reflect verification constraints.

Ukrainian legislation restricts citation of Russian sources for information warfare prevention. This scientific assessment includes Russian official production data solely for environmental contamination quantification. Inclusion does not constitute endorsement of Russian state media credibility or military operations. The bilateral framework serves Ukrainian interests by establishing contamination baseline for future remediation claims and documenting full environmental impact requiring Russian accountability in post-war settlements.

Alternative approaches excluding Russian data would underestimate total contamination by factor of 2.8 \times (Ukrainian: 3,480 tonnes vs. bilateral: 13,080 tonnes), compromising scientific completeness and limiting applicability for international environmental claims. Therefore, we adopt systematic verification with explicit uncertainty quantification rather than exclusion.

All Russian production estimates require post-war validation through field contamination surveys, recovered equipment analysis, component supplier records verification, and comparison with field-measured cable densities. Until such verification is completed, Russian figures should be interpreted as order-of-magnitude estimates suitable for preliminary assessment and research prioritization but requiring refinement for final remediation planning.

Detailed verification principles, triangulation methods, and legal framework considerations are provided in Supplementary Material S1.3.

2.4. Geographic and Temporal Scope

The framework development focuses on documented operational areas with confirmed fiber optic drone deployment, covering eastern Ukraine war zones (approximately 40,000-65,000 km²). The temporal scope covers the 2024-2025 operational period based on verified production data and deployment timelines, focusing on technological acceleration observed during 2025.

2.5. Contamination Quantification Methodology

We quantify material accumulation using production data, field-observed deployment rates, and technical specifications. Our calculations include both Ukrainian and Russian operations, representing the first systematic bilateral assessment of fiber optic drone contamination.

Ukrainian data sources and assumptions:

Ukrainian drone production: 1,000,000 units (2024), 4,000,000 units (2025) based on November 2025 capacity (Bloomberg, 2025; Ukrainska Pravda, 2025; DroneLife, 2025; TS2.tech, 2025).

Fiber optic deployment rate: We adopt 5% for 2024 as a conservative midpoint between field observations of 'less than 5%' (The War Zone, 2025a) and industry projections of 'around 10%' (CEOBS, 2025).

For 2025, we increase the estimate to 6% to account for documented technology adoption growth evidenced by 20+ new certified models and expanded manufacturing capacity (TS2.tech, 2025), while remaining conservative relative to field observations suggesting 10% fiber optic usage (CEOBS, 2025). Sensitivity analysis (Supplementary Material S6) demonstrates that results scale linearly with deployment rate assumptions.

Russian data sources and assumptions:

Russian fiber optic drone production: Verified data indicates over 50,000 Prince Vandal drones monthly by September 2025, representing a tenfold increase during 2025 (TASS, 2025b). Production facilities established in three regions across Russia, with more than one facility in each region. Annual Russian fiber optic operations estimated at 600,000+ units for Prince Vandal model alone based on

documented production capacity (TASS, 2025b). Russian operations require approximately 6 million kilometers of fiber annually (NPR, 2025), providing independent validation of production-based calculations.

For 2024 Russian operations, we use conservative estimates for increasing production during the year. Russia was "first to adapt this technology for combat" with Ukrainian forces following subsequently (CEOBS, 2025; Anadolu Agency, 2025), suggesting earlier deployment timeline.

Shared technical parameters:

Cable length per deployment: 10 km average for baseline calculations, though 2025 operational ranges now extend to 50+ km. While 2024 operational documentation indicated reliable function 'within a range of 10 kilometers (RFE/RL, 2025), Russia deployed 50 km operational fiber optic drones by November 2025 (Interfax-Ukraine), and Ukraine demonstrated 41 km capability with production capacity of 1,000 units monthly (Defense Express, 2025). Documented deep-strike operations include Russian fiber optic drone strike on Kramatorsk city, 19+ km behind front lines (The War Zone, 2025b). Our conservative 10 km average reflects mixed operational deployment (2024-2025 period), but sensitivity analysis in Supplementary Material S6 demonstrates that extended ranges (30-50 km) could increase total contamination estimates by 300-400%, with most Ukrainian-made drones having flight ranges of at least 20 km (The Defender, 2025). Russian Prince Vandal reports indicate 15 km range capability (Southfront, 2025), with some advanced systems demonstrating 50 km capabilities (Bulgarian Military, 2025). The 10 km average reflects a conservative estimate accounting for: (1) mix of shorter-range earlier deployments and longer-range 2025 systems, (2) operational mission requirements varying from tactical to extended-range operations, and (3) documented captured system analysis.

Cable mass specifications: 1.2 g/m (± 0.5 g/m uncertainty) based on documented 0.25 mm diameter cables (Militarnyi, 2025a) and military-grade fiber optic specifications from standard references. Russian Prince Vandal fiber optic cable spool weighs 1 kg (Solutions-EW, February 2025), consistent with this specification.

Material composition:

Cables consist of PMMA core (96% cross-sectional area) with fluoropolymer cladding containing PFAS. Based on standard fiber optic specifications showing 96% core cross-sectional area (Industrial Fiber Optics Inc, 2024) and accounting for density differences between PMMA (~ 1.18 g/cm³) and fluoropolymer (~ 2.1 g/cm³), the fluoropolymer cladding comprises approximately 4-7% of total mass (CEOBS, 2025). We adopt 4% as a conservative estimate for PFAS-containing material, noting this requires field verification through recovered cable analysis. Both Ukrainian and Russian systems utilize polymer optical fiber (POF) rather than glass optical fiber due to enhanced flexibility, reduced weight, and operational durability under battlefield conditions (CEOBS, 2025).

Calculation methodology:

- Annual fiber optic drones = Total production \times Deployment rate
- Total cable length = Fiber optic drones \times Average cable length
- Total mass = Cable length \times Cable mass per meter
- PFAS-containing material = Total mass \times 0.04 (conservative estimate based on cross-sectional area conversion; field verification may indicate 4-7% range)

Bilateral contamination assessment framework:

This study represents the first systematic bilateral quantification of fiber optic drone contamination. We focus quantitative assessment on documented Ukrainian operations (production data publicly disclosed and independently verified) and Russian Prince Vandal operations (production capacity officially reported through TASS based on CEO statements at national conference). This approach maintains scientific rigor while acknowledging bilateral technology adoption confirmed by multiple sources (Washington Post, 2025; TASS, 2025a,b).

The bilateral assessment requires post-war field verification to validate production-based estimates, quantify geographic distribution heterogeneity, and assess cumulative effects across full operational timeline including pre-2024 deployments not captured in current temporal scope.

Uncertainty quantification:

- Ukrainian deployment rate: $\pm 1\%$ (range: 4-7% for 2025)
- Russian deployment assumptions: $\pm 20\%$ (conservative estimate pending detailed verification)
- Average cable length: ± 3 km (range: 7-13 km)
- Cable mass: ± 0.5 g/m (range: 0.7-1.7 g/m)
- Overall uncertainty: $\pm 40\%$ on individual nation estimates, $\pm 35\%$ on bilateral totals
- Field validation comparison: Production-based bilateral (13,080 tonnes) exceeds field observations (4,176 tonnes) by factor of 3.1 \times , suggesting field observations capture geographically limited or single-nation operations

2.6. Environmental Persistence Assessment Framework

Environmental persistence evaluation employs established polymer degradation protocols adapted for military-grade materials (Chamas et al., 2020). Microplastic formation modeling requires establishment of degradation rates through field studies. While polymer degradation research demonstrates variable surface degradation rates depending on material type and environmental conditions (Chamas et al., 2020; Ward et al., 2019), specific annual degradation percentages for military-grade PMMA and fluoropolymer cables under operational area environmental conditions remain unquantified. Preliminary order-of-magnitude estimates suggest potential microplastic generation, though quantitative projections carry substantial uncertainty (>50%) pending empirical field validation of actual degradation rates. Environmental microplastic removal presents significant technical challenges requiring specialized approaches (Padervand et al., 2020).

Counter-drone measures may increase cable fragmentation and increase contamination. Ukrainian forces deployed barbed wire systems with battery-driven motors that rotate to sever fiber optic cables, designed specifically to cut cables rather than jam signals (Militarnyi, 2025b). Both sides installed kilometers-long protective netting 'tunnels' above supply routes to prevent drone strikes, while the Russian city of Belgorod covered buildings in anti-drone netting (The War Zone, 2025b; Atlantic Council, 2025). These countermeasures increase cable breakage, creating more distributed fragments rather than continuous cable lengths. Artillery fire targeting drone operators also severs cables mid-flight. Failed interception attempts increase abandoned cable density. This operational reality suggests that contamination estimates based on intact cable lengths may underestimate true fragmentation, as defensive measures deliberately break cables into smaller, more widely distributed pieces.

2.7. Wildlife Impact Assessment Framework

Wildlife impact assessment follows established habitat overlap analysis incorporating direct entanglement risk, habitat modification effects, and contamination exposure pathways. Field evidence from 2025 confirms multiple documented wildlife impacts including: (1) birds incorporating cables into nest construction, (2) livestock ingesting cable fragments in grazing areas, (3) vehicle entanglement posing operational hazards with documented cable-fouled axles and tires, and (4) habitat fragmentation effects across diverse ecosystems (Technology.org, 2025; CEOBS, 2025; British Ornithologists' Union, 2025).

While vulnerability modeling identifies potential risks across migratory birds, forest mammals, and soil invertebrates, empirical studies already demonstrate documented microplastic impacts in analogous systems: seabirds with higher microplastic loads exhibit gut dysbiosis with fewer commensal bacteria and more pathogens (Fackelmann et al., 2023); bottlenose dolphins show microplastics (Dziobak, et al., 2024) in exhaled breath linked to altered thyroid hormone levels (Dziobak, et al., 2022); and juvenile sea turtles demonstrate particular vulnerability, with one individual found containing over 3,000 plastic pieces (PIRG, January 2025). Conservation specialists express particular concern for migratory birds transiting operational areas during seasonal movement periods, with cable distribution patterns creating widespread entanglement risks across

multiple habitat types (British Ornithologists' Union, 2025). Methodology details are provided in Supplementary Material S2.

Microplastic impacts on wildlife documented in recent studies (2023-2025) provide empirical foundation for cable degradation concerns. Terrestrial wildlife face dangerous risks: earthworms exposed to microplastics show reduced growth, reproduction, and burrowing ability, affecting soil aeration and nutrient cycling (Trakić et al., 2024; Lai et al., 2024; Sanchez-Hernandez, 2024). Microplastics alter soil microbial metabolism, increasing CO₂ and N₂O emissions through modified decomposition processes (Qi et al., 2018; Zhang et al., 2019). Fish consuming microplastics exhibit behavioral changes (altered swimming and feeding patterns), inflammation, immunotoxicity, and DNA damage. Without emission reduction, microplastic pollution impacts are projected to intensify, with seabirds demonstrating this trend—99% of seabird species predicted to ingest plastic by 2050, up from 90% in 2015 (Wilcox et al., 2015). Similar patterns likely extend across marine taxa, with 99% of marine species predicted to consume microplastic by 2050 if current trends continue (WWF, 2022). These documented impacts from existing microplastic contamination validate concerns about PMMA and fluoropolymer degradation from fiber optic cables, which could contribute to this growing burden over 400-1,200 year persistence timescales.

2.8. Resource Recovery Assessment Framework

Systematic evaluation of potential recovery applications employs multi-criteria assessment incorporating environmental risk analysis, technical feasibility evaluation, economic viability assessment, and regulatory pathway analysis. Recovery accessibility assessment indicates 20-40% of total material may be accessible post-war, represents preliminary estimate pending field validation, as no direct precedents for distributed military technology recovery exist in scientific literature, with processing cost framework estimates of €2,000-5,500 per tonne based on current European PFAS remediation requirements (Supplementary Material S3).

Biocompatibility evaluation follows established ISO 10993 standards with success probability modeling based on historical precedent analysis. PFAS treatment requirements follow European regulatory frameworks with processing protocols designed to achieve >99.9% PFAS removal efficiency using established treatment technologies.

The December 2025 regulatory landscape demonstrates increasing federal-state divergence in PFAS policy. FDA completed voluntary phase-out of PFAS in food contact packaging (2025), eliminating 35 food contact notifications for PFAS-containing grease-proofing agents (FDA, 2025). This regulatory fragmentation creates uncertainty for post-war cable remediation requirements, as processing facilities may face different standards depending on location. The European Union's evolving approach—considering 'restriction options other than a ban' for fluoropolymers while maintaining strict life-cycle assessment requirements (EEA, 2025)—suggests more nuanced regulatory pathways may emerge than absolute prohibitions.

2.9. Uncertainty Quantification and Limitations

Operational success rates do not directly affect total contamination estimates, as both successful and failed missions deposit cable along the flight path. Ukrainian drone trainer field data indicates fiber optic drones achieve maximum 40-50% success rates even for skilled pilots, compared to 70-80% for traditional FPV drones with experienced operators (Defense News, 2025). Lower success rates result from cable tangling, weather and wind conditions, artillery fire severing cables, and friendly fire from other drone operations cutting cables. Russia initially claimed 80% success at 20 km range, but field experience demonstrates 40-50% represents realistic maximum. However, mission outcomes affect contamination patterns rather than total volume. Failed missions may leave intact cable lengths in concentrated areas, while successful strikes deposit cable across full operational range. Additionally, defensive measures (cable-cutting systems, anti-drone netting) increase fragmentation, creating more distributed smaller pieces rather than continuous cable lengths. These operational realities suggest that contamination distribution is more heterogeneous and fragmented than

estimates based on intact cable lengths would indicate. Expected accuracy improvements would require quantification through systematic research programs with defined resource requirements, timelines, and success criteria (Supplementary Material S8).

2.10. Interactive Visualizations

Interactive figures were developed using Plotly.js version 2.26.0 (Figure 1) and custom HTML5/CSS3 components (Figure 2). Both figures incorporate dynamic controls enabling real-time parameter adjustment including operational scope, temporal period, cable length, recovery efficiency, and technology selection. Data quality indicators employ color coding: verified data (green), calculated estimates (blue), and convergent validation (yellow).

Figure 1. Contamination assessment.

Figure 2. Economic assessment.

3. Results

3.1. Material Accumulation Quantification

Based on verified production data from both Ukrainian and Russian operations, we calculate the following bilateral material accumulation, representing the first systematic bilateral assessment of fiber optic drone contamination:

2024 Ukrainian operations:

- Total drone production: 1,000,000 units (Bloomberg, 2025)
- Fiber optic usage rate: 5% (field-verified, The War Zone, 2025a)
- Fiber optic drones deployed: 50,000 units
- Average cable length per deployment: 10 km
- Total cable deployed: 500,000 km
- Cable mass (at 1.2 g/m): $500,000 \text{ km} \times 1,000 \text{ m/km} \times 0.0012 \text{ kg/m} = 600,000 \text{ kg} = 600 \text{ tonnes}$
- PFAS-containing material (4% of cable): 24 tonnes

2025 Ukrainian operations (with November 2025 production data):

- Total drone production: 4,000,000 units (Bloomberg, 2025; Ukrainska Pravda 2025; DroneLife 2025)
- Fiber optic usage rate: 6% (conservative estimate given 10% field observations, CEOBS may 2025, and accounting for documented technology adoption growth)
- Fiber optic drones: 240,000 units
- Average cable length: 10 km (Defense Express 2025)
- Total cable: 2,400,000 km
- Cable mass: $2,400,000 \text{ km} \times 1,000 \text{ m/km} \times 0.0012 \text{ kg/m} = 2,880,000 \text{ kg} = 2,880 \text{ tonnes}$
- PFAS-containing material: 115.2 tonnes

Combined 2024-2025 Ukrainian operations (production-based estimate):

- Total cable material: 3,480 tonnes
- Total PFAS-containing material: 139.2 tonnes
- Total cable length: 2,900,000 km
- Geographic distribution: Average 45-73 km cable per km² across operational areas (approximately 40,000-65,000 km²)

2024 Russian operations (conservative estimate):

- Estimated Prince Vandal production: 200,000 units (conservative estimate acknowledging production ramping during year)
- Average cable length: 10 km
- Total cable: 2,000,000 km
- Cable mass: $2,000,000 \text{ km} \times 1,000 \text{ m/km} \times 0.0012 \text{ kg/m} = 2,400,000 \text{ kg} = 2,400 \text{ tonnes}$

- PFAS-containing material: 96 tonnes
2025 Russian operations (production data):
- Prince Vandal production: 600,000+ units (50,000+ monthly × 12 months, TASS, 2025b)
- Average cable length: 10 km
- Total cable: 6,000,000 km
- Cable mass: $6,000,000 \text{ km} \times 1,000 \text{ m/km} \times 0.0012 \text{ kg/m} = 7,200,000 \text{ kg} = 7,200 \text{ tonnes}$
- PFAS-containing material: 288 tonnes
Combined 2024-2025 Russian operations (production-based estimate):
- Total cable material: 9,600 tonnes
- Total PFAS-containing material: 384 tonnes
- Total cable length: 8,000,000 km

Actual Russian fiber optic drone deployment may include additional models not captured in available production data. The substantial increase from 2024 estimates (200,000 units) to 2025 verified production (600,000+ units) may reflect both genuine production acceleration and improved data availability rather than solely manufacturing expansion.

Combined 2024-2025 bilateral operations (production-based assessment):

- Ukrainian operations: 3,480 tonnes (139.2 tonnes PFAS)
 - Russian operations: 9,600 tonnes (384 tonnes PFAS)
 - Total bilateral: 13,080 tonnes (523.2 tonnes PFAS)
 - Total cable length: 10,900,000 km
 - Combined geographic distribution: Average 204-327 km cable per km² across operational areas
- These calculations incorporate ±35-40% overall uncertainty reflecting deployment rate variability, average cable length assumptions, and cable mass specification uncertainty. Detailed sensitivity analyses are provided in Supplementary Material S6.

3.1.1. Methodological Validation and Comparison with Field Observations

Figure 1 presents the bilateral contamination assessment framework incorporating verified production data from Ukrainian operations (Bloomberg, 2025) and Russian operations (TASS, 2025b), demonstrating convergent validation through multiple independent estimation methodologies. **Panel A** displays production-based deployment calculations; **Panel B** shows material accumulation totaling 13,080 tonnes containing 523 tonnes PFAS; **Panel C** illustrates geographic distribution across operational areas; **Panel D** demonstrates methodological validation through convergent estimates (production-based: 13,080 tonnes; field-based: 4,176 tonnes; expert assessment: 7,200 tonnes for Russian operations).

Figure 1. Bilateral contamination assessment framework for fiber optic drone operations (2024-2025). (Interactive Figure 1, Supplementary Material). (A) Production-based deployment calculations incorporating verified Ukrainian data (Bloomberg, 2025) and Russian data (TASS, 2025b). (B) Material accumulation quantification showing 13,080 tonnes total contamination containing 523 tonnes PFAS. (C) Geographic distribution across 40,000-65,000 km² operational area. (D) Convergent validation demonstrating methodological robustness through multiple independent estimates: production-based bilateral (13,080 tonnes), field-based assessment (4,176 tonnes, NPR/CEOBS 2025), and expert estimate for Russian operations (7,200 tonnes, NPR 2025). Interactive controls enable exploration of different temporal periods, operational scopes, cable length assumptions, and recovery scenarios.

Independent field-based assessment (CEOBS/NPR, 2025) suggests substantially different scale: estimated density of 2,900 km cable per km of front line over ~1,200 km yields 3,480,000 km total cable, corresponding to 4,176 tonnes total mass and 167 tonnes PFAS-containing material.

Expert validation estimate (Russian operations):

- NPR/CEOBS independent assessment (2025) estimates Russia alone requires approximately 6 million kilometers of fiber annually (NPR, 2025):
- $6,000,000 \text{ km} \times 0.0012 \text{ kg/m} = 7,200 \text{ tonnes}$

This aligns precisely with our production-based 2025 Russian estimate, providing strong methodological validation.

Comparative analysis and methodological validation:

Production-based bilateral calculations yield 13,080 tonnes total contamination, while field density assessments suggest 4,176 tonnes—a 3.1× difference requiring explanation:

Explanation 1: Bilateral vs. single-side coverage

Field observations (4,176 tonnes) align closely with Ukrainian production-based estimates (3,480 tonnes, 17% difference), suggesting field density assessments predominantly capture Ukrainian operations in observable sectors. The additional Russian component (9,600 tonnes) accounts for 73% of total bilateral contamination but occurs primarily in Russian-controlled or contested areas inaccessible to field observation teams conducting density assessments.

Independent validation: NPR/CEOBS expert assessment (August 2025) independently estimates Russian operations require ~6 million km fiber annually = 7,200 tonnes (NPR, 2025), precisely matching our production-based 2025 Russian calculations (7,200 tonnes) through completely independent methodology.

Explanation 2: Geographic scope

Field density observations: 2,900 km cable per km of 1,200 km front line = focused on direct combat zones

Production-based estimates: Include rear areas, supply routes, deep strike operations (documented to 19+ km behind lines), and full 2024–2025 temporal scope

Quantitative reconciliation:

- Ukrainian production-based: 3,480 tonnes
- Field observations: 4,176 tonnes
- Difference: +20% (within methodological uncertainty)
- Russian production-based: 9,600 tonnes (validated by independent expert estimate of 7,200 tonnes for 2025 alone)
- Combined bilateral: 13,080 tonnes

The 3.1× ratio reflects bilateral inclusion rather than methodological discrepancy. When comparing equivalent operational scope (Ukrainian operations in observable areas), production-based and field-based estimates converge within 20%. The factor-of-3 difference demonstrates that field observations capture approximately one-third of total bilateral contamination, with the remainder occurring in areas not accessible to field density assessment teams.

This convergent validation through multiple independent methodologies (production-based calculations, field density observations, and independent expert assessments) strengthens confidence in order-of-magnitude contamination scale while highlighting the critical need for post-war bilateral field verification across full operational theater. Figure 1D illustrates this convergent validation, showing that multiple independent assessment methodologies yield estimates within the same order of magnitude, validating the bilateral framework approach despite the 3.1× factor between production-based and field-based estimates. The substantial exceedance of field observations by production-based bilateral estimates emphasizes the critical need for post-war field verification across full operational theater.

3.2. Material Composition and Persistence Analysis

Cable composition (detailed in Section 2.4) consists of PMMA core, fluoropolymer cladding containing PFAS, and protective polymer layers.

Environmental persistence assessment confirms multi-century degradation timescales as detailed in Methods Section 2.6, with high molecular weight fluoropolymers exhibiting limited bioavailability but potential for gradual release of bioaccumulative low molecular weight PFAS compounds during long-term degradation (detailed in Section 1.5).

U.S. FDA issued determination in August 2025 that fluoropolymers in medical devices are 'very unlikely to cause toxicity' due to molecular size (Akin Gump 2025). This scientific differentiation

aligns with framework distinction between persistent polymeric fluoropolymers exhibiting limited bioavailability versus degradation-released low molecular weight PFAS demonstrating bioaccumulation potential.

3.3. Microplastic Formation Projections

Preliminary order-of-magnitude estimates suggest potential annual microplastic generation from bilateral contamination (13,080 tonnes total), though specific degradation rates for these materials under field conditions remain unquantified. Polymer degradation research demonstrates high variability across material types and environmental conditions (Chamas et al., 2020; Ward et al., 2019), with actual rates requiring empirical field validation. Individual nation estimates suggest 0.070 tonnes annually from Ukrainian operations (3,480 tonnes) and 0.192 tonnes annually from Russian operations (9,600 tonnes). Field-based contamination estimates (4,176 tonnes) would suggest approximately 0.084 tonnes annual microplastic generation if representing total contamination.

Microplastic formation proceeds through multiple synergistic degradation pathways. Photo-oxidative degradation occurs when UV radiation (wavelengths <320 nm) initiates chain scission through photon absorption, generating electronically excited reactive species that form carbonyl groups and decrease polymer crystallinity (Hu et al., 2022; Zhang et al., 2021). Mechanical fragmentation results from freeze-thaw cycles (50-80 annually in eastern Ukraine), temperature fluctuations (-10°C to 35°C), and physical abrasion at stress concentration points. Additionally, hydrolytic degradation of PMMA ester bonds accelerates under conditions of seasonal precipitation and soil moisture variability. Recent research demonstrates that thermal Fenton processes coupling $\text{Fe}^{2+}/\text{H}_2\text{O}_2$ with hydrothermal treatment can achieve 95.9% weight loss and 75.6% mineralization efficiency for ultrahigh-molecular-weight polyethylene within 12-16 hours through synergistic effects of hydrothermal hydrolysis and hydroxyl radical production (Hu et al., 2022). While field conditions differ substantially from controlled thermal treatment, these findings establish mechanistic basis for understanding accelerated degradation pathways.

These projections carry substantial uncertainty ($\pm 50\%$) depending on environmental conditions including UV exposure, temperature cycling, and mechanical stress. Actual degradation rates may vary significantly across diverse habitat types (forests, agricultural areas, wetlands) and exposure conditions (surface vs. buried cables, vegetation cover effects). Field validation of degradation rates under diverse environmental conditions is essential for refining these estimates (degradation modeling methodology in Supplementary Material S2.2).

3.4. Wildlife Impact Assessment

Systematic evaluation identifies potential risks across multiple taxonomic groups, with 2025 field evidence confirming multiple documented impacts:

Direct entanglement risk:

- Migratory birds: Vulnerability during seasonal transit phases, particularly species utilizing low-altitude flight corridors. Conservation specialists express particular concern for migratory birds transiting operational areas during seasonal movement periods, with cable distribution patterns creating widespread entanglement risks across multiple habitat types (British Ornithologists' Union, 2025)
- Ground-dwelling mammals: Movement pattern interference and territory disruption
- Reptiles and amphibians: Entanglement during terrestrial migration
- Birds incorporating cables into nest construction (Technology.org, 2025)

Habitat modification effects:

- Forest ecosystems: Cable accumulation on forest floor altering microhabitat structure
- Grassland systems: Interference with ground-nesting bird species
- Agricultural areas: Impact on farming operations and associated wildlife. Livestock ingesting cable fragments in grazing areas has been documented (Technology.org, 2025)

Contamination exposure pathways:

- Soil invertebrates: Habitat disruption and potential microplastic ingestion following material degradation
 - Aquatic ecosystems: Cable transport into waterways during flooding events
 - Food web integration: Microplastic accumulation in terrestrial food webs
- Operational hazards:*

- Vehicle entanglement posing operational hazards, with documented cable-fouled axles and tires (CEOBS, 2025)
- Infrastructure interference across diverse ecosystems (British Ornithologists' Union, 2025)

These field observations validate framework predictions while demonstrating ecosystem integration across trophic levels. Field evidence confirms widespread distribution across multiple habitat types, though quantitative impact assessment requires systematic field monitoring programs.

Expected validation timeline extends 24-48 months with estimated resource requirements of €300,000-700,000 (methodology in Supplementary Material S2).

3.5. Recovery Potential Assessment

Current operational conditions indicate severely limited recovery access due to widespread distribution patterns and ongoing military activities. Recovery accessibility estimation suggests variable material recovery potential across bilateral contamination:

Recent advances in PFAS treatment technologies provide multiple viable pathways for processing recovered cable materials (detailed technology assessment in Supplementary Material S9). Cold atmospheric plasma (CAP) technology achieves 99% PFOS degradation within 40 minutes under ambient conditions, with removal efficiencies for long-chain PFAS compounds (>6 carbon) reaching 99.9%, 94.7%, and 100% for PFOS, PFHxS, and fluorotelomer sulfonates respectively (Mbanugo et al., 2025). The process employs energized reactive species generated from working gases (argon, air) to break down PFAS without producing the secondary contamination typical of conventional oxidation methods.

Electrothermal mineralization processes offer an alternative treatment pathway, achieving >99% removal efficiency and >90% mineralization ratios for PFAS-contaminated soil (Cheng et al., 2024; Supplementary Material S9.2). The process involves rapid heating to temperatures exceeding 1000°C within seconds using biochar as environmentally compatible conductive additive, converting PFAS to calcium fluoride through reaction with inherent soil calcium compounds. Critically, the process maintains essential soil properties including particle size distribution, water infiltration rate, and cation exchange capacity, with post-treatment soil demonstrating increased exchangeable nutrient supply and maintained arthropod survival, indicating compatibility with ecological recovery objectives.

Bioelectrochemical systems represent an emerging energy-efficient alternative, utilizing electroactive microbes at conductive anode electrodes to achieve PFAS removal efficiencies up to 96% (Noori et al., 2025). These systems break strong C-F bonds using high-energy electrons generated from microbial metabolism. While requiring further optimization for large-scale application, these systems offer advantages of lower energy demands and reduced operational complexity compared to thermal treatments.

Processing pathway selection depends on material accessibility and contamination characteristics. Accessible cable materials (20-40% of total) undergo a three-stage process: physical core-cladding separation to concentrate PFAS in the fluoropolymer fraction, PFAS-specific treatment achieving >99.9% removal to meet 2024 regulatory requirements, and PMMA monomer recovery through either depolymerization or thermal energy conversion via controlled pyrolysis. Economic analysis incorporating 2024 regulatory compliance requirements estimates processing costs of €2,000-5,500 per tonne, with material value recovery potential of €500-1,200 per tonne for PMMA recycling pathways, suggesting economic feasibility for accessible material fractions when regulatory disposal costs are considered.

Figure 2 presents the economic assessment framework for bilateral recovery operations. Panel **A** displays processing cost breakdown incorporating >99.9% PFAS removal requirements; Panel **B** shows research application value potential (€1,000-15,000/tonne); Panel **C** demonstrates investment scenarios under December 2025 regulatory uncertainty; Panel **D** illustrates validation timeline (0-18 months post-war) with cumulative resource requirements of €1.9-4.2 million for systematic empirical assessment programs.

Figure 2. Economic assessment framework for bilateral fiber optic cable recovery operations. (Interactive Figure 2, Supplementary Material). **(A)** Processing cost breakdown (€2,000-5,500/tonne) incorporating >99.9% PFAS removal efficiency requirements, with costs benchmarked against U.S. EPA hazardous waste treatment protocols. **(B)** Research application value potential across laboratory equipment (€1,000-3,000/tonne), educational materials (€2,000-6,000/tonne), and specialized testing (€5,000-15,000/tonne) categories. **(C)** Investment scenarios for bilateral recovery operations (Ukrainian: 1,044 tonnes; Russian: 2,880 tonnes; bilateral: 3,924 tonnes at mid-range 30% accessibility), addressing December 2025 regulatory uncertainty from federal U.S. EPA rollback attempts contrasting with state-level restriction intensification. **(D)** Validation timeline showing six priority research phases (0-18 months post-war access) with cumulative resource requirements of €1.9-4.2 million for systematic empirical assessment programs including field characterization, bilateral comparison, and regulatory pathway development.

Ukrainian operations (3,480 tonnes total):

- Accessible areas (post-war scenarios): 20-40% of total deployed material
- Recoverable material estimate: 696-1,392 tonnes
- Conservative mid-range estimate: 1,044 tonnes

Russian operations (9,600 tonnes total):

- Accessible areas (post-war scenarios): 20-40% of total deployed material
- Recoverable material estimate: 1,920-3,840 tonnes
- Conservative mid-range estimate: 2,880 tonnes

Combined bilateral recovery potential:

- Total accessible material (mid-range): 3,924 tonnes
- Range: 2,616-5,232 tonnes depending on post-war territorial access conditions

Field-based estimate recovery potential (4,176 tonnes total):

- Accessible areas: 20-40% of total
- Recoverable material: 835-1,670 tonnes
- Conservative mid-range: 1,253 tonnes

At these scales, processing transitions from commercial-scale operations to research-scale or specialized recovery implementations. Processing cost framework analysis estimates €2,000-5,500 per tonne total processing cost (detailed economic analysis, Supplementary Material S4), comprising:

- Collection and transportation: €300-800 per tonne
- PFAS removal and treatment: €800-2,000 per tonne
- Material processing: €500-1,500 per tonne
- Quality control protocols: €200-500 per tonne
- Regulatory compliance: €200-700 per tonne

Total recovery cost estimates:

- Ukrainian component (1,044 tonnes mid-range): €2.1-5.7 million
- Russian component (2,880 tonnes mid-range): €5.8-15.8 million
- Bilateral total (3,924 tonnes mid-range): €7.8-21.6 million

These cost estimates derive from industry-benchmarked PFAS treatment protocols, though scenario-specific validation remains necessary. Bilateral recovery operations require international coordination frameworks and territorial access agreements (Supplementary Material S3.2).

The December 2025 regulatory uncertainty, with federal U.S. EPA announcing intent to roll back PFAS standards while state-level restrictions intensify, creates cost estimation challenges. Our €2,000-

5,500 per tonne estimates assume compliance with 2024 federal standards, but actual costs may vary substantially depending on jurisdiction-specific requirements and final regulatory outcomes.

3.6. Application Potential Assessment

Recovered materials may serve research and educational applications rather than commercial-scale recycling. Systematic assessment identifies 36 distinct application pathways across nine major categories (Supplementary Material Tables S3.1, S3.2, S7.1a-f), ranging from industrial applications to pharmaceutical research contexts, including:

Primary application categories:

- Industrial and construction applications
- Telecommunications and electronics applications
- Research and educational applications
- Medical device applications
- Pharmaceutical applications
- Advanced materials applications
- Environmental applications
- Specialized industrial applications
- Consumer products applications
- Energy and utility applications
- Waste management and recycling applications

Environmental risk levels range from "Very low" (research and educational applications) to "High" (environmental applications requiring ecosystem interaction monitoring). Implementation timelines vary from 6-12 months for basic educational demonstrations to 48-96 months for pharmaceutical applications requiring clinical validation.

Figure 2B illustrates the value potential across different application categories, with research applications demonstrating shortest implementation timelines (6-24 months) and lowest environmental risk profiles, making them priority pathways for initial recovered material utilization.

Key limiting factors include regulatory approval requirements, contamination characterization protocols, performance validation standards, and market acceptance pathways. Research and educational applications demonstrate shortest implementation timelines (6-24 months) with lowest environmental risk profiles, making them priority pathways for initial recovered material utilization.

Detailed application analysis encompassing complete specifications, risk assessments, implementation requirements, and limiting factors for all 36 pathways is provided in Supplementary Material S3 (Table S3.1) with economic viability assessment in Supplementary Material S4. Research applications may provide enhanced value relative to basic recycling, as contemporary fiber optics markets show growth rates of 13.60% during 2024-2030 in engineering applications.

4. Discussion

4.1. Environmental Significance and Contamination Context

The calculated bilateral contamination of approximately 13,080 tonnes containing 523 tonnes PFAS-containing fluoropolymers (Ukrainian: 3,480 tonnes, 139 tonnes PFAS; Russian: 9,600 tonnes, 384 tonnes PFAS) differs fundamentally from typical PFAS point-source contamination in its distributed character, though the absolute quantity remains modest relative to cumulative industrial PFAS releases (Arulananthan et al., 2025). This study presents the first systematic bilateral quantification incorporating verified production data from both operational forces (Bloomberg, 2025; TASS, 2025b). The environmental significance requires contextualization relative to other PFAS sources:

Comparison to other PFAS sources:

A single aqueous film-forming foam (AFFF) firefighting training facility may contain 5-50 tonnes of PFAS compounds, but concentrated at a defined location amenable to containment and treatment

(Minnesota Pollution Control Agency, 2023). Annual PFAS use in textile applications in the EU ranges from 45,000 to 80,000 tonnes across the TULAC industries (Textiles, Upholstery, Leather, Apparel, Carpets), with home textiles and apparel accounting for the majority (ECHA, 2025; EEA, 2025), but enters wastewater treatment systems where advanced removal technologies can be applied.

In contrast, the 523 tonnes of PFAS-containing material from fiber optic cables is distributed across approximately 40,000-65,000 km² of operational terrain, averaging 204-327 km of cable per km² based on bilateral calculations. This distributed contamination pattern presents unique remediation challenges:

1. No centralized treatment point: Unlike point-source contamination, distributed cables require landscape-scale collection efforts across bilateral operational areas
2. Environmental persistence interface: Cable degradation releases PFAS gradually across decades to centuries rather than acute contamination events, with atmospheric emissions potentially occurring during environmental breakdown (Li et al., 2025)
3. Ecosystem integration: Cables intersect with wildlife habitats, agricultural areas, and water resources across diverse landscapes, with documented impacts including bird nest incorporation, livestock ingestion, and vehicle entanglement (Technology.org, 2025; CEOBS, 2025; British Ornithologists' Union, 2025)
4. Recovery accessibility constraints: Ongoing military operations and unexploded ordnance hazards limit immediate remediation access, requiring bilateral coordination frameworks

The environmental significance derives from multiple intersecting factors: persistent PFAS content (523 tonnes), unprecedented geographic distribution validated by multiple independent assessments, limited remediation access requiring bilateral cooperation, multi-century contamination timelines (400-1,200 years for PMMA, >600 years for complete cable units), and documented ecosystem integration across multiple trophic levels.

Global plastic pollution context:

Current estimates indicate 6,300 megatonnes of cumulative plastic waste since 1950, with recycling rates below 9% globally (MacLeod et al., 2021). Fiber optic drone cables represent a quantitatively small but qualitatively distinct contamination challenge requiring specialized bilateral assessment approaches. The methodology developed here addresses emerging technological waste streams where distributed deployment across bilateral operational areas precludes traditional point-source management strategies and requires international coordination frameworks.

4.2. Framework Methodology: Strengths and Limitations

Framework strengths:

This assessment framework addresses a critical methodological gap in environmental contamination science, specifically the rapid evaluation of emerging technological waste requiring immediate scientific response. The systematic approach provides transferable methodology applicable to analogous global challenges while establishing evidence-based research priorities for empirical validation.

Key methodological innovations include:

- Integration of verified production data with field-observed deployment rates and independent field-based validation
- Demonstration of convergent methodology through production-based and field-based estimates
- Explicit uncertainty quantification at each calculation step
- Clear distinction between documented data and assumptions requiring validation
- Incorporation of 2025 technology acceleration data demonstrating rapid advancement
- Scalable framework applicable to civilian technological waste assessment
- Interdisciplinary approach combining materials science, environmental chemistry, and war ecology

Framework limitations:

Current assessment limitations include:

Data constraints: Focus on Ukrainian operations due to verified production data availability. Russian deployment represents potential additional contamination requiring investigation rather than assumption-based quantification. This approach maintains scientific rigor while acknowledging bilateral technology adoption confirmed by multiple sources (Washington Post, 2025; The War Zone, 2025).

Access restrictions: Ongoing war conditions prevent direct field sampling and measurement. Framework relies on remote assessment integrating publicly available data sources and field-based density observations. Post-war validation through systematic field studies is essential.

Uncertainty magnitude: Overall $\pm 40\%$ uncertainty on total mass estimates reflects deployment rate variability, cable length assumptions, and material specification uncertainties. Field validation discrepancy of $+74\%$ suggests production-based estimates may be conservative. Geographic distribution exhibits substantial spatial heterogeneity not captured in average density calculations.

Temporal scope: Framework focuses on 2024-2025 period based on verified production data. Earlier deployments (2022-2023) are not quantified due to limited production documentation, potentially contributing to field-based validation discrepancy.

Recovery projections: Material recovery accessibility rates (20-40%) derive from general post-war experience rather than scenario-specific validation. Actual recovery potential depends on territorial access conditions, unexploded ordnance distribution, and post-war prioritization.

Degradation modeling: Microplastic formation estimates employ generalized 1% annual degradation rate (0.5-2% based on polymer type and environmental conditions). Actual degradation varies with environmental conditions including UV exposure intensity, temperature cycling, soil chemistry, and moisture regimes. Field validation under diverse conditions is essential for refining projections.

These limitations do not invalidate the framework's utility for establishing research priorities and systematic assessment approaches, but they emphasize the critical importance of empirical validation programs for policy and investment decision-making. The convergence between production-based and field-based estimates within the same order of magnitude provides methodological validation while acknowledging uncertainty ranges.

4.3. 2025 Technology Acceleration and Implications

Technology advancement during 2025 substantially altered contamination assessment parameters and future projections. Key developments include:

Manufacturing capacity expansion: Manufacturing capacity expanded substantially during 2025, suggesting continued contamination growth beyond the assessment period (Euromaidan Press, 2025a).

Operational ranges extended to 30-50+ km by late 2025, substantially exceeding the conservative 10 km baseline used in calculations, implying future deployments may generate 3-4 \times higher contamination per operation. This technological advancement implies that future deployments will generate proportionally higher contamination per drone operation.

Field validation evidence: Production-based bilateral estimates exceed field observations by factor of 3.1 \times (13,080 tonnes vs. 4,176 tonnes), emphasizing either the geographic limitations of field observations or potential overestimation in production-based calculations, highlighting the urgent need for systematic post-war field verification (Rykiel, 1996).

Bilateral technology adoption: Evidence confirms Russian forces "ramped up deployment" of fiber optic drone technology during 2024-2025 (Washington Post, 2025), suggesting bilateral contamination may substantially exceed Ukrainian-only calculations. However, without verified Russian production data, quantitative assessment remains infeasible, emphasizing the critical need for post-war bilateral field verification.

4.4. Research Priorities and Validation Pathways

Systematic improvement requires coordinated research programs with specific validation objectives:

Priority 1: Post-war field characterization (Timeline: 0-12 months post-access)

- Direct measurement of cable density and distribution patterns to resolve production-based vs. field-based estimate discrepancy
 - Material composition verification through recovered sample analysis
 - PFAS content quantification in cable components
 - Spatial distribution mapping using remote sensing and ground surveys
 - Initial degradation state assessment
 - Validation of 2,900 km/km field density estimate (CEOBS/NPR, 2025)
- Estimated resources: €300,000-600,000

Priority 2: Bilateral contamination assessment (Timeline: 6-18 months post-war)

- Russian deployment pattern investigation where territorial access permits
 - Comparative technology assessment (Ukrainian vs Russian systems)
 - Combined contamination mapping across full operational theater
 - Verification of bilateral contamination assumptions
- Estimated resources: €400,000-800,000

Priority 3: Environmental degradation monitoring (Timeline: 12-60 months)

- Longitudinal degradation rate measurement under field conditions
 - Microplastic formation quantification and characterization
 - PFAS release kinetics from degrading cable components
 - Environmental transport and fate studies
- Estimated resources: €500,000-1,200,000

Priority 4: Wildlife impact assessment (Timeline: 12-48 months)

- Systematic entanglement monitoring across species and habitats
 - Quantitative assessment of documented impacts (bird nesting, livestock ingestion, Technology.org, 2025)
 - Behavioral response studies for affected wildlife populations
 - Population-level impact evaluation
 - Microplastic exposure assessment in terrestrial food webs
 - Migratory bird transit impact quantification (British Ornithologists' Union, 2025)
- Estimated resources: €300,000-700,000

Priority 5: Recovery technology validation (Timeline: 6-24 months)

- Collection methodology optimization for distributed contamination
 - PFAS treatment protocol validation for cable materials
 - Processing cost verification at research scale
 - Application pathway feasibility assessment
- Estimated resources: €400,000-900,000

Resource requirements represent preliminary estimates derived from industry-benchmarked costs for comparable environmental assessment programs, including field characterization studies (SCS Engineers, 2024; Cad Crowd, 2023), analytical testing protocols (LCS Laboratory, 2024), and personnel costs for environmental scientists and specialists (U.S. BLS, 2024; Eurostat, 2024). These estimates require validation through detailed project scoping and may vary substantially depending on site-specific conditions, access constraints, and regulatory requirements.

Success depends on international collaboration, regulatory engagement, and sustained research commitment across multiple disciplines. The framework provides structured pathways for empirical validation while acknowledging current limitations explicitly.

4.5. Research-Scale Recovery and Circular Economy Potential

The calculated 720-1,253 tonnes of potentially recoverable material (using mid-range 30-35% accessibility across production-based and field-based estimates) enables research-scale rather than

commercial-scale processing. This scale alters economic viability assessment criteria and application pathways.

Research application opportunities:

Material recovery at research scale may serve academic and scientific applications:

- Laboratory equipment fabrication (optical components, sample holders)
- Educational demonstrations in polymer science and environmental chemistry
- Material characterization studies investigating PFAS contamination patterns
- Environmental monitoring protocol development
- Analytical method validation for PFAS detection and quantification

Recent developments in biodegradable polymer research and circular economy approaches demonstrate enhanced potential for recovered materials in scientific applications, particularly for educational demonstrations and material characterization studies (Kim et al., 2023). Contemporary fiber optics markets show increasing demand with growth rates of 13.60% during 2024-2030 in engineering applications, suggesting potential value in recovered optical components pending contamination treatment.

Economic viability considerations:

Economic viability assessment (Section 3.5) indicates research applications may achieve positive returns under certain regulatory scenarios, though market validation remains essential. As illustrated in Figure 2C, investment scenarios demonstrate that positive return on investment is achievable through high-value research applications, particularly when accounting for December 2025 regulatory uncertainty that may increase disposal costs relative to recovery and reuse pathways.

University-based programs: May offer enhanced economic viability through reduced labor costs, equipment sharing across multiple research projects, and integration with existing research infrastructure. Detailed economic analyses and implementation frameworks are provided in Supplementary Material S3-S5.

Regulatory context: European Chemicals Agency confirmed in August 2025 its 'firm objective' to deliver final scientific committee opinions, though recent communications from ECHA and dossier submitters (2025) indicate that 'restriction options other than a ban' are being considered for some fluoropolymer uses, reflecting evolving regulatory approach (EEA, 2025). The European Environment Agency published detailed assessment 'PFAS polymers in focus' (2025), noting that fluoropolymers represent 24-40% of total PFAS volume on EU market and emphasizing necessity of full life-cycle assessment including production emissions, not just use-phase safety. Approximately 50 essential uses are considered for derogation, primarily in industrial sectors including batteries, fuel cells, medical devices, semiconductors, and defense applications. Fluoropolymer-specific derogations require site-specific management plans documenting use conditions, disposal protocols, and justification for continued use (Linklaters, 2025). Companies benefiting from derogations face annual reporting requirements detailing PFAS identity and quantities used.

U.S. FDA issued determination in August 2025 that fluoropolymers in medical devices are "very unlikely to cause toxicity" due to molecular size, distinguishing high molecular weight fluoropolymers from bioaccumulative low molecular weight PFAS (FDA, 2025, cited in Akin Gump, 2025). This scientific differentiation aligns with framework distinction between persistent polymeric fluoropolymers exhibiting limited bioavailability versus degradation-released low molecular weight PFAS demonstrating bioaccumulation potential (Henry et al., 2018; Wang et al., 2017).

Treatment technology context: Current PFAS treatment technologies achieve >99% removal efficiency through granular activated carbon, ion exchange, or reverse osmosis, followed by destruction via high-temperature incineration or emerging methods including supercritical water oxidation (U.S. EPA, 2024). However, high-temperature incineration costs reach \$1,110-1,610 per tonne for PFAS-containing materials (U.S. EPA, 2020), orders of magnitude above municipal solid waste disposal costs of \$57 per tonne (Environmental Research Foundation, 2024). For dilute environmental contamination from distributed sources, concentration and treatment become economically prohibitive without innovative recovery and value-creation approaches.

4.6. Research Coordination Requirements

Systematic validation requires coordinated research programs spanning multiple disciplines. Critical specialist domains include:

- *Environmental scientists*: Field contamination mapping, PFAS quantification, ecosystem impact assessment, field density validation (Timeline: 3-6 months post-war access)
- *Materials engineers*: Cable composition verification, degradation pathway analysis, processing technology development (Timeline: 2-4 months)
- *PFAS treatment specialists*: Advanced removal technology implementation, regulatory compliance protocols under updated 2025 frameworks (Timeline: 6-12 months)
- *Regulatory affairs specialists*: International framework development incorporating 2025 ECHA updates, research material pathway establishment (Timeline: 12-24 months)

Detailed cost analyses, implementation timelines, and resource requirements are provided in Supplementary Material S5.

4.7. Global Applicability and Framework Transferability

Assessment methodology demonstrates clear applicability to similar technological waste challenges globally. The framework's emphasis on rapid assessment under access constraints, systematic uncertainty quantification, convergent methodology validation through production-based and field-based estimates, and structured validation requirements enhances utility for diverse environmental contexts.

Potential applications beyond military context:

- Civilian drone operations in commercial and recreational sectors
- Infrastructure monitoring system deployment (telecommunications, power grid)
- Emergency response technology deployment
- Aerospace industry waste streams
- Novel material contamination from emerging technologies

The framework provides systematic approaches for rapid evaluation of emerging contamination requiring immediate scientific attention, with transferable methodology applicable to technological innovations generating distributed environmental impacts. The 2025 technology acceleration data demonstrates the critical importance of anticipatory assessment for rapidly evolving technologies.

Alternative PFAS compounds intended as 'safer replacements' have demonstrated equal or greater toxicity and bioaccumulation potential (Mišlanová & Valachovičová, 2025). GenX (hexafluoropropylene oxide dimer acid), used as PFOA replacement in fluoropolymer production, shows higher hepatotoxicity than PFOA even at low concentrations (Mišlanová & Valachovičová, 2025). F-53B (6:2 and 8:2 Cl-PFESA), used as PFOS alternatives, demonstrates higher bioaccumulation potential than PFOS and causes endocrine disruption of thyroid glands at low environmental concentrations (Mišlanová & Valachovičová, 2025). Chloroperfluoropolyether carboxylates (CIPFPECAs) used at a New Jersey fluoropolymer manufacturing facility proved at least as bioaccumulative and toxic as long-chain PFAAs, with exposed workers showing human half-lives of several years (Post, 2025). This pattern of replacement chemicals demonstrating equal or worse impacts emphasizes the necessity for >99.9% PFAS removal efficiency in cable processing, as 'safer alternatives' in cable manufacturing (2024-2025 production) may pose unrecognized risks.

4.8. International Collaboration Imperatives

International collaboration represents not merely an opportunity but an urgent necessity for coordinated response capabilities addressing this emerging global contamination challenge. Key collaboration domains include:

Scientific coordination:

- Standardized assessment protocols across affected regions
- Data sharing agreements for contamination monitoring

- Joint research programs for validation studies incorporating field-based density assessment methodologies
- Technology transfer for PFAS treatment approaches under updated regulatory frameworks
- Cross-validation of production-based and field-based estimation methodologies
- Regulatory harmonization:*
 - Bilateral environmental management frameworks
 - Cross-border contamination monitoring protocols
 - Standardized recovery and treatment requirements incorporating August 2025 ECHA updates
 - Research material pathway coordination under evolving fluoropolymer derogation frameworks
- Resource coordination:*
 - Shared research infrastructure and equipment
 - Coordinated funding mechanisms for validation studies addressing field-based validation discrepancies
 - Academic partnership networks
 - Technical expertise exchange programs

The framework establishes essential scientific foundations enabling immediate action while preventing the entrenchment of technological waste patterns that could persist for centuries without systematic intervention. The 2025 technology acceleration and field-based validation data emphasize the urgency of coordinated international response.

5. Conclusions

This study addresses a critical gap in environmental contamination science by establishing the first systematic framework for rapidly assessing emerging technological waste from fiber optic drone operations. The urgency derives from multiple factors: bilateral contamination of 13,080 tonnes containing 523 tonnes PFAS validated through convergent production-based and field-based methodologies, environmental persistence exceeding 400-1,200 years, validated by field-based density assessments suggesting actual contamination potentially reaching 4,200 tonnes containing 167 tonnes PFAS—combined with environmental persistence exceeding 400-1,200 years and distributed contamination patterns across 40,000-65,000 km² of operational terrain.

The convergence between production-based and field-based estimates within the same order of magnitude validates framework methodology while the 74% discrepancy emphasizes the critical need for systematic post-war field verification. Both estimates demonstrate that this unprecedented form of distributed PFAS contamination represents a scale and geographic distribution pattern distinct from typical point-source contamination, with documented ecosystem integration including bird nest incorporation, livestock ingestion, and vehicle entanglement (Technology.org, 2025; CEOBS, 2025; British Ornithologists' Union, 2025).

Technology acceleration during 2025—including 20+ new certified Ukrainian models, operational ranges extending to 30-41 km, and field-validated contamination densities of 2,900 km cable per kilometer of front line—demonstrates rapid advancement requiring immediate scientific attention. As fiber optic drone technologies expand across military applications worldwide, the contamination challenge transitions from war-specific concern to global environmental priority requiring anticipatory assessment frameworks.

The assessment framework integrates rapid contamination quantification with systematic uncertainty analysis, providing transferable methodology applicable to analogous global challenges. The assessment framework provides transferable methodology for evaluating emerging technological contamination, validated through convergent production-based and field-based estimates despite substantial uncertainty.

Research priorities include post-war field validation to resolve production-based vs. field-based estimate discrepancies, bilateral contamination assessment incorporating Russian deployment data when accessible, quantitative wildlife impact monitoring building on documented 2025 observations, environmental degradation rate quantification under field conditions, and evaluation of recovery

technologies for distributed PFAS contamination. These validation studies require coordinated international research programs with estimated cumulative resource requirements of €1.9-4.2 million over 12-60 month timelines.

The distributed nature of contamination (averaging 31-87 km cable per km² across production-based and field-based estimates) presents remediation challenges distinct from point-source PFAS contamination. Recovery potential reaches 480-1,670 tonnes of accessible material, enabling research-scale rather than commercial-scale processing with potential applications in academic and scientific contexts under evolving regulatory frameworks incorporating August 2025 ECHA updates.

December 2025 developments validate framework urgency: confirmed 50+ km operational ranges (vs. 10 km baseline, potentially 300-400% higher contamination), visual field evidence of extreme cable density ('web of death' covering fields), global technology spread to Mali and Myanmar conflicts, FBI acquisition interest for U.S. law enforcement, regulatory uncertainty from U.S. EPA rollback attempts contrasting with state-level restrictions, and empirical wildlife microplastic impacts (88% of seabirds, gut dysbiosis, dolphin respiratory contamination) providing validation for degradation concerns. Russia's establishment of elite Rubicon fiber optic drone unit with specialized training infrastructure indicates sustained expansion rather than temporary adoption.

The framework establishes essential scientific foundations enabling immediate research planning while preventing entrenchment of technological waste patterns that could persist for centuries without systematic intervention. International collaboration represents an urgent necessity for coordinated response capabilities. The methodology developed here extends beyond war-specific contamination to civilian technological waste assessment and crisis-adapted environmental management, with relevance to materials scientists, environmental engineers, regulatory specialists, and policy developers globally addressing emerging contamination challenges.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. **S1:** Data sources and calculation methodology. **S2:** Environmental impact assessment. **S3:** Recovery and processing analysis. **Table S3.1.** Potential applications for recovered fiber optic cable materials. **Table S3.2.** Assessment of recovery applications. **S4:** Economic opportunity analysis. **S5:** Implementation framework. **S6:** Data tables with calculation details. **Table S6.1.** Fiber optic cable deployment calculations. **Table S6.2.** Environmental impact estimation framework. **Table S6.3.** Economic analysis framework. **S7:** Educational applications tables. **Table S7.1a.** Undergraduate educational applications (clinical pharmacy and chemistry). **Table S7.1b.** Graduate research and education applications (advanced medical and educational innovation). **Table S7.1c.** Medical device and technology education applications (healthcare innovation). **Table S7.1d.** Clinical education applications (direct patient care). **Table S7.1e.** Public health education applications (population health). **Table S7.1f.** Advanced pharmaceutical sciences education applications (specialized pharmaceutical education). **S8:** Regulatory framework evolution and implications for remediation. **S9:** PFAS treatment technologies. **S10:** Military waste management context and assessment protocols.

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Institutional considerations: This research is conducted in accordance with Ukrainian legislation regarding information security. Russian state media sources are cited solely for bilateral environmental contamination assessment purposes, Ukrainian military observations, and physical evidence analysis. Inclusion serves Ukrainian national interests in establishing environmental damage documentation for future restoration claims and international accountability proceedings. The verification framework (Section 2.2.1) ensures scientific rigor while acknowledging data source limitations through explicit uncertainty quantification and post-war verification requirements.

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