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# Tracing the Untraceable: A Review and Discussion on the Forensic Attribution of 3D-Printed Firearms

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## ABSTRACT

The rise of 3D-printed firearms (3DPFs) presents challenges for forensic science, law enforcement, and regulation. Unlike traditional weapons, 3DPFs can be manufactured using consumer-grade additive manufacturing systems and open-source designs, with the absence of serial numbers limiting traceability. Unconventional and inconsistent toolmarks produced during manufacture and firing complicate forensic attribution, or association, to specific printers and restrict linking bullets and cartridge cases to individual 3DPFs. Since 2021, prevalence has increased globally, with UK cases rising by 733% between 2021 and 2023. This work examines: (1) the expanding threat from 3DPF-related crime, (2) forensic challenges in linking 3DPFs to printers and ammunition, and (3) advances in quantitative identification. Conventional firearm examination techniques, particularly those relying on rifling impressions, are often unsuitable for fused deposition manufactured 3DPFs, which commonly use plastic or improvised smooth-bore barrels. Although firing marks can transfer to ammunition, their distinctiveness and reproducibility vary with design and manufacturing method, limiting reliability. Alternative approaches include analyzing nozzle drag marks, deposition striae, and base-plate marks for printer attribution, although variability in printers, parameters, materials, wear, and subclass characteristics may affect robustness. Spectroscopic and mass-spectrometric techniques show promise for detecting polymer and gunshot residues, including hybrid polymer–primer particles, but datasets remain limited. The UK's shift towards quantitative reporting has driven research into methods such as micro-CT, geometric measurement, and Congruent Matching Cells for conventional firearms; however, these remain underexplored for 3DPFs. Overall, attribution is feasible but complex, requiring continued interdisciplinary research and robust, 3DPF-specific forensic protocols.

## 1 | Introduction

The advent of 3D-printed firearms (3DPFs) has added a complex and disruptive dimension to contemporary debates surrounding gun control, public safety, and the regulation of emerging technologies (Daly et al. 2021). In contrast to traditionally manufactured firearms, 3DPFs are becoming increasingly accessible, often producible with basic equipment, limited technical expertise, and minimal oversight. This ease of production allows individuals to circumvent existing regulatory frameworks, raising profound safety and legal concerns. The proliferation of these so-called "ghost guns", unserialized, and potentially untraceable weapons, poses significant challenges not only for public safety but also for forensic science, law enforcement, and policymakers (DOJ 2023). Unlike conventional firearms, where tracing a weapon back to its

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original manufacturer is often of limited evidential value beyond class-level information, 3D-printed firearms introduce an additional layer of forensic complexity. In 3DPF cases, attribution may require linking recovered weapons or ballistic evidence not only to prior incidents but potentially to a specific printer or residual trace evidence left at a scene. This investigative challenge is analogous to examples seen in United Kingdom casework involving converted blank-firing or imitation firearms, where forensic examinations have extended beyond the weapon itself to include comparisons with tools, jigs, or manufacturing artifacts recovered from conversion workshops. As such, potential attribution does not rely solely on conventional ballistic evidence but integrates toolmark, residual trace evidence, and manufacturing-process indicators to establish links between weapons, individuals, and locations. Similarly, 3DPF investigations may require consideration of manufacturing processes and artifacts alongside traditional forensic evidence, reflecting a shift towards the reconstruction of decentralized, small-scale production environments. Current research on the forensic attribution of 3D-printed firearms is examined in Section 3, following an overview of the development of 3DPFs and their increasing domestic and international significance. This trajectory underscores the scale of the emerging problem and highlights the need for continued and targeted forensic research.

### 1.1 | Methods of 3D-Printing

Additive manufacturing (AM), or 3D-printing, is a layer-by-layer fabrication process in which physical objects are built directly from digital designs. While AM includes a range of technologies with differing materials and processing methods, all systems rely on a computer-assisted design (CAD) file that is translated into G-code via slicing software to guide material deposition during printing. Only a limited subset of AM technologies is routinely encountered in forensic investigations involving 3DPFs and associated components, which are outlined here (Redwood et al. 2018; Day and Speers 2020):

- Material Extrusion (MEX)/Fused Deposition Manufacturing (FDM)/Fused Filament Fabrication (FFF). MEX is the most commonly encountered AM process in forensic casework due to its low cost, ease of use, and widespread domestic availability (Dass 2025; Schaufelbühl 2025). Thermoplastic filaments such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and nylon are heated and extruded through a nozzle, depositing material layer-by-layer. MEX is frequently used to manufacture structural 3DPF components (e.g., frames or receivers), and the extrusion process produces deposition marks and toolpath artifacts that may have evidential value for printer or process attribution (Pavlovich and Garrison 2023; Clifton et al. 2026).
- Stereolithography (SLA), or Vat Photopolymerisation (VP)/Digital Light Synthesis (DLS). Within a vat of photopolymer, a laser (for SLA) or digital light projector (for DLS) is used to cure liquid resin into a hardened plastic layer-by-layer. Although less common for load-bearing firearm components due to material brittleness, SLA printing may be relevant where smaller components or decorative accessories are encountered and has been used to make prototypes (King and McDonald 2015). It has also been used to print propellant for 3DPFs (Yang et al. 2020).
- Selective Laser Sintering (SLS)/Powder Bed Fusion (PBF). A laser is used to fuse powdered materials such as nylon, metals, thermoplastic polyurethane (TPU), polyether ether ketone (PEEK) into solid objects, layer by layer. Although the equipment cost limits accessibility, SLS has been documented in the production of high-strength firearm prototypes, suppressor components, and accessories (King and McDonald 2015; Li et al. 2021).

### 1.2 | Development of 3D-Printed Firearms

The history of 3DPFs is a story of rapid technological innovation, legal controversy, and evolving societal concerns. Whilst 3D-printing was first developed in the late 1980s, the field gained global attention in 2013 with the release of the "Liberator," the first fully 3D-printed gun, capable of firing 380 ACP caliber cartridges. Blueprints were downloaded over 100,000 times within days, sparking widespread debate and regulatory action. Media coverage rapidly framed the weapon as an untraceable and undetectable "ghost gun," raising concerns about circumvention of firearms licensing, export controls, and metal-detection systems. In response, the U.S. State Department intervened within days, invoking the Arms Export Control Act (AECA) and International Traffic in Arms Regulations (ITAR) to force the removal of the files on the basis that their online dissemination constituted the unlawful export of controlled technical data. This action initiated a prolonged legal and political dispute encompassing federal export regulation and state-level public safety considerations. Furthermore, it raised constitutional questions surrounding freedom of expression, including whether CAD files should be regarded as protected "speech". Although a 2018 settlement permitted the publication of the Liberator blueprints, subsequent state-level legislative action resulted in renewed attempts at restrictions. However, the rapid initial dissemination of the files both online and through alternative distribution channels has meant that such regulatory responses have largely occurred after the fact, with the designs remaining readily accessible despite ongoing legislative efforts (Defense Distributed v. United States Department of State 2017; Emerson and Bensley 2019; Schaufelbühl et al. 2023; Tan et al. 2023). Despite the recognized importance of digital blueprint dissemination in enabling 3DPF manufacture, there is currently little published data quantifying trends in the seizure or recovery of such files. This is likely due to the fact that digital blueprints are typically identified as part of broader criminal investigations and are not consistently recorded or reported as discrete seizure categories. The blueprints' rapid dissemination online catalyzed a wave of new designs (Figure 1) (Pavlovich 2019; Jenzen-Jones and Senft 2023; van der Heide 2023), and there are now in excess of 2100 3DPF plans available on the internet (Schaufelbühl et al. 2023). The proliferation of 3DPF blueprints has led to a global debate about the implications of digital weapon manufacturing and finding the right regulatory balance between safety, misuse of technology and innovation (Heckmann 2020; Tan et al. 2023).



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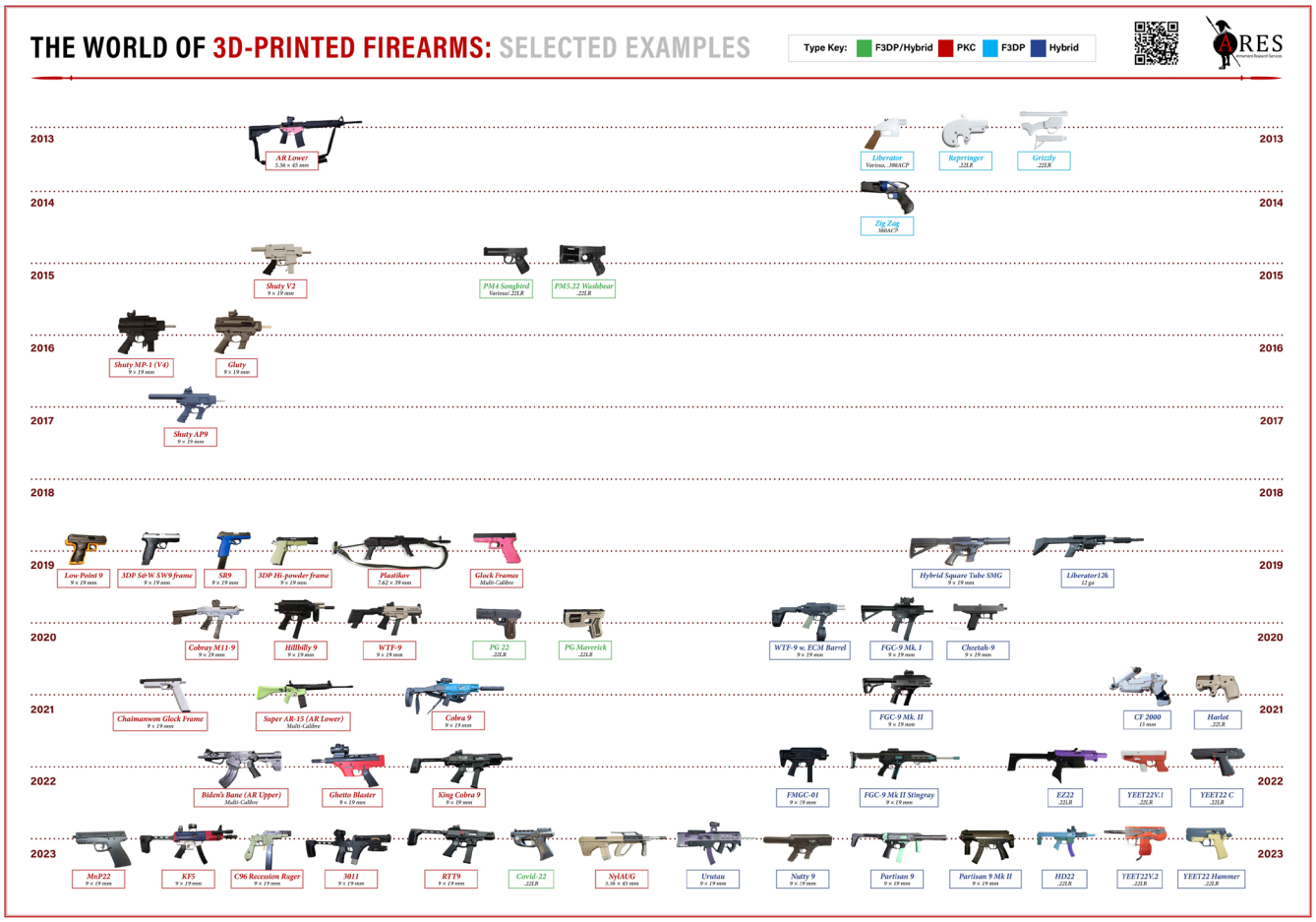


**FIGURE 1** | Timeline of selected 3DPF emergence and evolution. PKC = Parts Kit Completions/Conversions, F3DP, Fully 3D-Printed Firearms (image shared with permission, from Jenzen-Jones and Senft (2023)).

Early models of 3DPFs were single-shot, typically equipped with smooth-bore, unrifled barrels, requiring manual extraction of fired cartridge cases, and often failed after a single discharge. However, advancements in design and manufacturing have significantly increased their sophistication and durability (Figure 1). When present, rifled barrels in 3DPFs are typically metallic rather than polymer (Li et al. 2021). However, designs such as the Deterrence Dispensed .22 Long Rifle AR-style pistol are fitted with rifled barrels printed from PLA (Hays 2020). Depending on the design, rifling may be inherent to a barrel printed entirely in metal or achieved in metal tubes purchased from hardware stores by methods such as electrochemical machining (ImproGuns 2017). When combined with appropriate print quality, polymer structural properties, and ammunition propellant loads, a number of prominent 3DPF designs, such as the FGC-9, Urutau, and the .22LR pistol described above, have been demonstrated to withstand repeated self-loading firing with limited structural degradation. Of these, the Urutau has also been reported as capable of fully automatic fire in its original configuration (Jenzen-Jones and Senft 2023; Veilleux-Lepage and Furedi 2025). In contrast, the FGC-9 can achieve fully automatic operation if fitted with a modified AR-15 trigger group (Jenzen-Jones and Senft 2023). The FMGC-01, released in 2022, is fitted with a selector switch allowing both semi- and fully-automatic firing (Jenzen-Jones and Senft 2023). Kshetri and Voas (2024) reported a recent development of blueprints to print plastic blocks, also known as auto sears or "switches", that transform pistols into fully automatic sub-machine guns, where 100 switches can be printed in 72 h on a standard 3D printer.

3DPFs now represent a significant subset of privately manufactured firearms (PMFs) and can be classified into three main categories (Jenzen-Jones and Senft 2023):

- Fully 3D-printed firearms (F3DPFs), which contain only very minor non-printed parts, such as a firing pin. These types of 3DPF are fitted with a typically smooth-bore polymer barrel.
- Hybrid 3DPFs, which are a combination of 3D-printed parts and non-restricted metal components such as springs and metal tubing acting as a barrel.
- Firearms with a 3D-printed receiver only, which are also known as Parts Kit Completions/Conversions, where the frame and receiver are 3D-printed, but all other parts are commercially available firearms components, including rifled barrels.

This literature review surveys the emerging, yet still relatively limited, body of academic and policy-oriented research on 3DPFs. It focuses on three interrelated areas: (1) the domestic and international threat landscape associated with 3DPF



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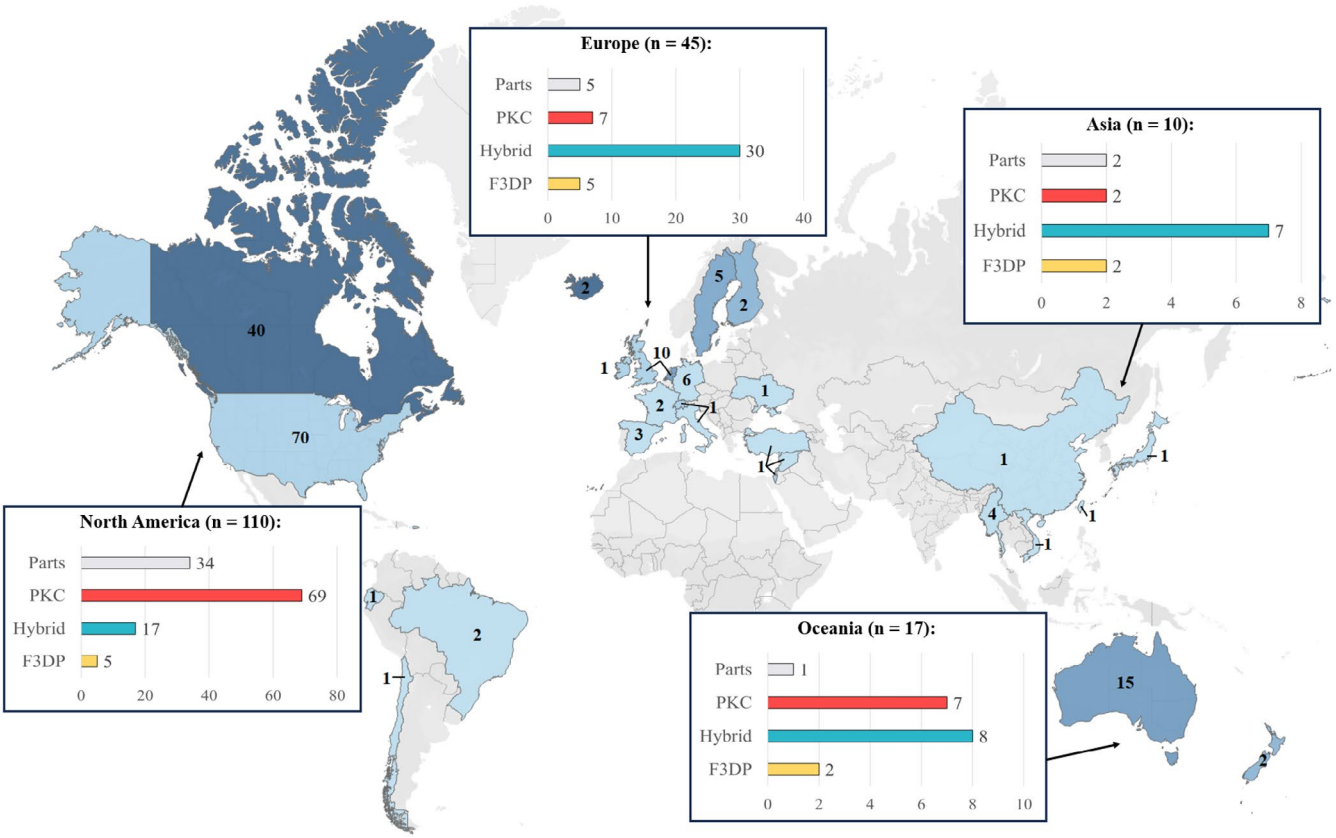


**FIGURE 2** | Cases involving 3DPFs, or 3DPF parts per 100,000 population. The numbers inside countries represent the total number of cases. The blue color gradient of a country reflects the total number of cases per 100,000 population, with darker shades indicating higher case rates. The information boxes provide information within the global regions regarding the types of items documented. PKC, Parts Kit Completions/Conversions; F3DP, Fully 3D-Printed Firearms (image shared with permission, from Schaufelbühl et al. (2024)).

criminality, (2) the forensic challenges of attributing 3DPFs to both their printer of origin and the ammunition they discharge, and (3) the development and application of quantitative methods for identifying and analyzing 3DPFs. Through analysis of current findings, this review intends to highlight critical knowledge gaps, evaluate the evolving capabilities of forensic tools, and provide insight into the broader implications of this rapidly advancing technology.

## 2 | Domestic and International Landscape

### 2.1 | 3D-Printed Firearm Prevalence

Collecting data on 3DPFs is extremely challenging due to underreporting, differences in the classification of these types of firearms, and the absence of a systematic reporting framework (Dass 2025; Veilleux-Lepage 2024). In addition, police and international security agencies often do not make data on weapons seizures publicly available. Schaufelbühl et al. (2024) conducted an analysis of 186 cases involving 3D-printed firearms (3DPFs) based on open-source data from the Clear Web, covering the period between 2014 and August 2023 across four global regions: North America, Europe, Asia, and Oceania (Figure 2). The study documented a marked increase in reported incidents from 2021 onward. A similar upward trend was identified by Dass (2025), who examined 225 3DPF-related incidents from 2013 to July 2024, also using keyword searches on Clear Web search engines. Veilleux-Lepage (2024) further contributed to the discourse by investigating the relationship between 3DPFs and radical factions, though his study focused exclusively on the period from January 2017 to June 2024 and limited analysis to ideological use cases. A common limitation highlighted across all three studies is the absence of a standardized reporting framework for 3DPF incidents. Although there is likewise no mandated reporting framework for conventional firearms, established international mechanisms and data-collection protocols, such as those developed under the United Nations Firearms Protocol adopted in 2001 and implemented from 2005, provide a consistent basis for classifying and reporting conventional firearm cases. Moreover, due to the long history, broadly recognizable forms, and typical material characteristics of conventional firearms, their classification is far less prone to inconsistency or misidentification. In contrast, the diverse materials and often unconventional designs of 3DPFs increase the likelihood of inconsistent classification by frontline officers, analysts, or media sources. This disparity underscores why the need for a dedicated, standardized reporting framework is significantly more pressing for 3D-printed firearms than for traditional ones.

The resourcefulness of the criminal fraternity in circumventing firearms legislation, restrictions, and tracking mechanisms is well documented in the literature, particularly in jurisdictions with stringent gun control measures. For many years, converted



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**TABLE 1** | Reported trends in 3D-printed firearms across global jurisdictions.

| Region/country | Metric | Value | | | Source |
|---|---|---|---|---|---|
| | | 2021 | 2022 | 2023 | |
| USA | "Ghost gun[a]" recoveries | 8500 | 19,273 | 25,785 | ATF 2024; DOJ 2023 |
| Globally | Documented cases | ~20 | ~57 | ~70 | Dass 2025 |
| Asia | % documented cases | | | 4[b] | Dass 2025 |
| Australia | % documented cases | | | 7[b] | Dass 2025 |
| Europe | % documented cases | | | 27[b] | Dass 2025 |
| North America | % documented cases | | | 49[b] | Dass 2025 |
| South America | % documented cases | | | 4[b] | Dass 2025 |
| Canada | % analyzed firearms | 0.5 | 0.5 | 8.7 | Ducharme et al. 2025 |
| United Kingdom | Seizure cases | 3 | 17 | 25 | NCA 2025 |
| Global | Documented cases | 41 | 75 | 47 (to August) | Schaufelbühl et al. 2024 |
| Asia | Documented cases | | | 10[c] | Schaufelbühl et al. 2024 |
| Europe | Documented cases | | | 45[c] | Schaufelbühl et al. 2024 |
| North America | Documented cases | | | 110[c] | Schaufelbühl et al. 2024 |
| Oceania | Documented cases | | | 17[c] | Schaufelbühl et al. 2024 |
| Europe | Documented cases | | | 44[d] | Schroeder et al. 2023 |
| North America | Documented cases | | | 108[d] | Schroeder et al. 2023 |

[a]"Ghost gun" recoveries in the USA include several types of privately made or unserialized firearms, including 3DPFs. It is not known how many of the figures reported here are specifically 3DPFs.
[b]The cases documented in this source were recorded between 2013 and July 2024. The number documented for each year for each region was not presented in this source. Documented cases had been identified on open-source information available on the Clear Web.
[c]The cases documented in this source were recorded between 2014 and August 2023. The number documented for each year for each region was not presented in this source. Documented cases had been identified on open-source information available on the Clear Web.
[d]The cases documented in this source were recorded between 2014 and 2023. The number documented for each year was not presented in this source. Documented cases had been identified via the Incident Monitor on Gunviolence.eu.

blank-firing weapons have served as a popular alternative to original lethal-purpose (OLP) firearms. Despite their reduced reliability, structural integrity, and safety, their relative ease of acquisition has often outweighed the challenges associated with sourcing genuine firearms in a tightly regulated market. (Hannam 2010; King and Florquin 2018; Mattijssen et al. 2023; Yalçın Sarıbey and Hannam 2009).

As outlined by Dass (2025), building 3DPFs is increasingly viewed as a more accessible alternative to converting blank-firing weapons, particularly when considering the required skill level, equipment, and technical knowledge. Converting a blank-firing weapon into a functional firearm typically demands somewhat specialized metalworking tools, machining skills, and a sound understanding of firearm mechanics to ensure the weapon can withstand the pressures of live ammunition without catastrophic failure. In contrast, 3D-printing significantly lowers these barriers. With only a consumer-grade 3D-printer, free or low-cost software, and access to tried and tested open-source design files, individuals with minimal technical background can theoretically produce functional firearm components in the comfort of their own home, albeit with the caveat that it still requires time and experimentation. The process often involves basic digital literacy and a rudimentary understanding of printer calibration rather than hands-on gunsmithing or fabrication. Dass (2025) further emphasizes that using 3D-printing makes gunsmithing a more discreet and self-contained method of illicit firearm production. Murphy (2025) discusses that as designs become more refined and widely shared online, and as the technology improves, the entry threshold for producing 3DPFs continues to decrease and that ultimately a 3DPF will be on par with an OLP firearm.

Recent evidence indicates a gradual but consistent increase in the detection and seizure of 3DPFs across multiple jurisdictions, although their operational use in crime remains limited in some regions and the methodology in data capture varies across the literature. Table 1 outlines these trends and measurement metrics, which are discussed in more detail below.

The first public criminal prosecution in the United Kingdom involving a 3DPF occurred in 2019 when Tendai Muswere became the first person convicted for manufacturing a weapon using a consumer-grade 3D-printer, following his arrest in 2017. He pleaded guilty to manufacturing and possessing frames for both a James R Patrick PM522 "Washbear" revolver and a Reprringer V3 "Hexen" pepper-box handgun (NABIS Annual Report 2019; National Crime Agency 2018; Sky News 2019). The National Crime Agency (2024, 2025) reported no confirmed incidents involving discharged 3DPFs during 2023–2024. However, seizure



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data demonstrate a notable upward trajectory, rising from 3 cases in 2021 to 17 in 2022 and 25 in 2023, representing a 733% increase over a two-year period. Of the 2023 cases, five involved complete firearms. This trend aligns with patterns identified by Schaufelbühl et al. (2024) and Dass (2025), suggesting that while use remains limited, availability and production are increasing. With this upward trend, it is reasonable to anticipate that the prevalence of 3DPFs will continue to increase as the technology advances, and that any changes will be monitored by the National Ballistics Intelligence Service (NABIS 2021).

Despite this growth, the NCA (2025) attributes the relatively low adoption of 3DPFs among UK criminal actors to perceived issues with reliability, build quality, and status when compared with OLP firearms or converted blank-firing weapons. Indeed, 2024 marked a notable shift in the UK firearms landscape, with converted blank-firing weapons surpassing OLP firearms in use for the first time. Broader firearms trends remain ambiguous: the NCA reported a 6% increase in firearms offenses between 2022–23 and 2023–24, whereas the Office for National Statistics (ONS 2025) documented a 20% decrease between 2023 and 2024. These discrepancies likely reflect differences in reporting periods, definitions, and classification practices, particularly regarding imitation firearms. Nevertheless, both agencies highlight the continued significance of non-traditional firearms within the UK context.

In Canada, the proportion of 3DPFs in analyzed firearms rose from 0.5% (2020–2022) to 8.7% in 2023 (Ducharme et al. 2025). In the United States, law enforcement agencies reported substantial growth in the seizure of "ghost guns," increasing from 8500 recoveries in 2020 to 19,273 in 2021, with 25,785 domestically recovered in 2022 (DOJ 2021, 2023; ATF 2024). However, the proportion of these that constitute true 3DPFs remains unclear due to inconsistent classification. Across Europe the prevalence of wholly or partially 3DPFs is on the rise, exacerbated by the ease of access to affordable printers and freely accessible blueprints (Duquet and Auweele 2021; European Union Agency for Law Enforcement Cooperation 2025). Here, 44 confirmed cases were documented between 2014 and 2023, accounting for 24% of global cases (Schroeder et al. 2023). The absence of standardized reporting frameworks continues to limit comprehensive assessment across EU member states. However, differences in reported case numbers between jurisdictions should be interpreted with caution. Higher reporting rates in certain regions, such as the United States, do not necessarily reflect greater underlying prevalence of 3DPFs. Rather, these disparities may be influenced by a combination of factors, including population size, law enforcement practices, seizure and reporting mechanisms, and classification frameworks. Variations in data availability and transparency across jurisdictions may further affect the apparent geographic distribution of cases.

Collectively, these findings suggest that while absolute numbers remain relatively low in many regions, the increasing availability of affordable 3D printing technologies and accessible digital blueprints is contributing to a steady rise in 3DPF-related activity. As proposed by Barton (2019), this trend is likely to continue, potentially increasing the prevalence of such weapons in criminal contexts and presenting ongoing challenges for forensic investigation and law enforcement.

## 2.2 | 3D-Printed Firearm Regulation

It could be argued that existing laws governing firearm manufacture already apply to 3DPFs (Walther 2015), and indeed the UK's principal legislation, the Firearms Act 1968, already encompasses such weapons under Section 57(1), which defines a firearm broadly enough to include 3D-printed variants. Consequently, no statutory amendment has been made specifically for 3DPFs; however, the Home Office Guide on Firearms Licensing Law has been updated to explicitly reference them (Home Office 2026). While this approach avoids unnecessary legislative duplication, it also highlights that the principal regulatory challenges posed by 3DPFs lie less in the classification of the finished weapon and more in the governance of digital design files or the printer itself, areas where existing firearms legislation provides only partial coverage.

On the 5th December 2025, the Border Security, Asylum and Immigration Act (2025) received Royal Assent in the United Kingdom. Part 3, Section 52 criminalizes the possession of 3D-printer firearm templates, provided that this is in circumstances that give rise to a reasonable suspicion that the template will be used in connection with any serious offense. Section 53(2) goes on to define a 3D-printer firearms template as "any document that may be used in conjunction with a 3D printer to produce any part of a firearm (as defined by Section 57 of the Firearms Act 1968)". This provision represents a notable attempt to move upstream by targeting digital precursors rather than completed weapons, and in principle offers law enforcement an earlier point of intervention. However, its effectiveness is likely to be constrained by evidential and definitional challenges, particularly in establishing intent and in distinguishing prohibited templates from benign CAD files. In practice, meaningful enforcement would likely require the development and maintenance of mechanisms for prohibited-template identification and tracking, including an authoritative database capable of being updated rapidly in response to emerging design iterations. Such agility is necessary given the capacity of online communities to refine, remix, and disseminate functional improvements at speed, often outpacing formal regulatory responses.

Comparative experience suggests that such definitional issues are a recurrent weakness in template-focused legislation. For instance, Pavlovich (2019) highlights that the 2015 amendment to Australia's Firearms Act 1996, which introduced a 14-year custodial penalty for possessing digital firearm blueprints, has prompted significant legal debate. Much of this centres on the conceptual extension of firearm definitions to digital objects and virtual representations, raising concerns about legal certainty (Adams 2020). While severe penalties may have symbolic or deterrent value, their practical enforceability remains questionable where files are easily encrypted, modified, or shared across jurisdictions. Taken together, these examples suggest that criminalization of digital templates is a necessary but insufficient measure when deployed in isolation, particularly in the absence of clear technical thresholds or harmonized definitions.



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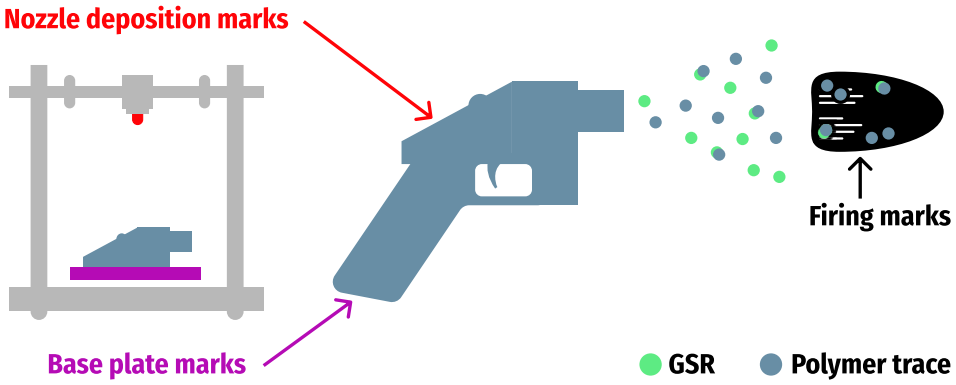


**FIGURE 3** | Schematic outlining some potential links between a 3D-printed firearm and its source printer, or to a specific crime scene. The firearm could potentially be linked to the 3D-printer via the nozzle deposition (red) or base-plate marks (purple) imparted to the firearm during manufacture. In addition, items from the scene could be attributed to the firearm, after it's been fired, via residual trace polymer evidence (blue), potential hybrid polymer-gunshot residues (represented by overlapping GSR (green) and polymer (blue) circles) and firing marks on fired bullets (white) and cartridge cases.

More promising are regulatory approaches that seek to disrupt the broader ecosystem enabling 3D-printed firearms rather than focusing exclusively on digital files. Tan et al. (2023) propose a three-pronged framework aimed at regulating 3DPFs while preserving civil liberties, democratic values, and technological advancement. Of the three elements proposed, tightening restrictions on the sale and purchase of propellant appears the most immediately enforceable, as this ammunition component remains subject to physical supply chains and existing regulatory infrastructure. This approach has gained further support from Dass (2025), who highlights the operational dependency of 3DPFs on conventional ammunition. In the UK context, these controls are already partially realized through Section 35 of the Violent Crime Reduction Act 2006 and the Firearms Act 2023, which criminalizes possession of ammunition components with intent to manufacture.

It could be argued that a similar rationale could apply to primers, although the UK has already introduced restrictions through Section 35 of the Violent Crime Reduction Act 2006, which regulates their sale and purchase. Additionally, the Firearms Act 2023 introduced a new offense: possessing component parts of ammunition with the intent to manufacture, explicitly including both propellant and primers. These measures arguably represent a practical choke-point that avoids some of the technical and civil liberties concerns associated with monitoring digital design files. In contrast, the other elements of Tan et al.'s framework raise more substantial practical and normative challenges. Firmware-level detection of firearm-related files by 3D-printer manufacturers may be undermined by the ease with which files can be renamed, fragmented, or modified, and may disproportionately affect legitimate research, prototyping, or educational uses. Similarly, the creation of registries linking printer ownership to identifiable individuals could face resistance on privacy and proportionality grounds, while offering limited investigative value given the availability of second-hand markets and shared or institutional printers. These measures, while conceptually attractive, therefore appear more difficult to operationalize effectively without generating significant unintended consequences.

Global legislative responses to 3DPFs are emerging, albeit unevenly (Daly et al. 2021). The rapid evolution of 3D-printing technology poses significant challenges for law enforcement and regulatory bodies worldwide. The European Commission's (2026) proposal to introduce EU-wide offenses targeting the illicit creation, possession, and dissemination of 3DPF blueprints marks an important step towards harmonization. Its emphasis on minimum custodial thresholds, cross-border cooperation, and improved data collection addresses a clear weakness in existing national approaches (European Commission 2026). However, without parallel reforms in intellectual property and online intermediary regulation, blueprint controls risk being displaced rather than resolved.

## 3 | 3D-Printed Firearm Attribution

While the popular press often describes 3DPFs as "untraceable," this characterization warrants scrutiny. This section examines the limited but growing body of academic literature that explores methods for attributing 3DPFs either to their source printer or to a specific crime scene via physical evidence (Figure 3). These studies challenge the notion of complete anonymity by detailing forensic techniques and investigative approaches that can potentially link printed components to a specific source.

### 3.1 | Digital Forensics

Digital forensics can play a significant role in investigations involving 3DPFs, particularly where devices, storage media, or networks are seized and may contain STL files, slicer profiles, or residual G-code. However, its applicability is highly contingent on the availability and integrity of digital evidence. In many operational casework contexts, such data may be deleted, encrypted, remotely hosted, or absent, limiting its evidential value. Digital forensics may, in some cases, provide the most direct evidential link between suspect and manufacture; however, this may not always be the case, reinforcing the need for robust physical evidence approaches. Rather than overlooking digital forensics, this review positions it as a complementary investigative pathway. The focus of this review is therefore deliberately confined to forensic attribution based on physical evidence, including 3D-printing marks, residual trace polymer analysis,



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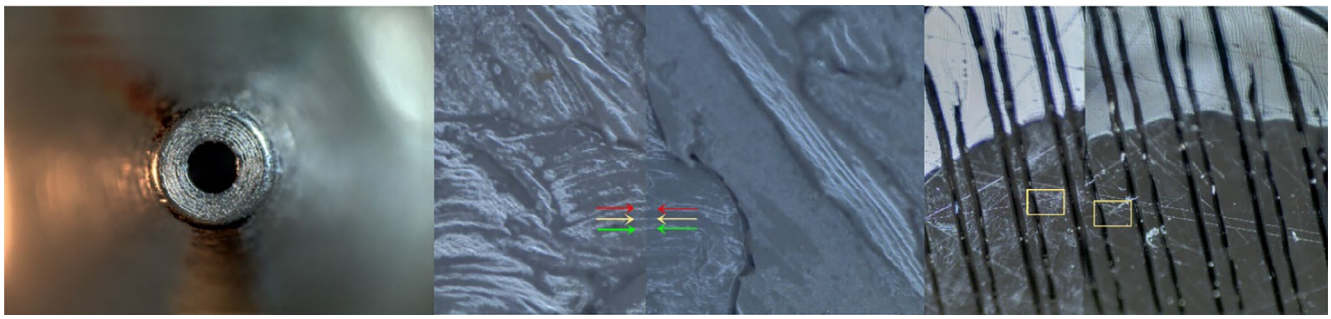

**FIGURE 4** | Left: Microscopic surface manufacturing markings and defects around the nozzle from a Bambu Lab P1S printer. Centre: Comparison of deposition striae on the surface of two 3D printed objects—the colored arrows highlighting corresponding similar striae. Right: Comparison of base plate marks on the underside of two 3D printed objects—the yellow box highlighting an area of corresponding similar markings.

hybrid polymer–gunshot residue, and firing-related toolmarks, which may remain recoverable even where digital evidence is unavailable, compromised, or not retained.

### 3.2 | 3D-Printing Marks

Studies have investigated techniques for analyzing hardware and process-induced imperfections in 3D-printers, which manifest as identifying features on printed objects and may serve as forensic markers. However, the forensic relevance of these techniques, particularly in the context of 3DPFs, may vary considerably depending on the nature of the signature, the required capture conditions, and the condition of the recovered exhibit. Among these, surface texture analysis has emerged as a leading approach for source attribution under controlled conditions. For instance, Shim et al.'s (2023) CFTNet uses fine, periodic surface features, arising from hardware imperfections and process variations, to distinguish between printers. Similarly, Li et al.'s (2018) PrinTracker uses commodity scanners to capture microscopic discrepancies in line formation, achieving up to 92% accuracy in printer attribution, even under challenging conditions. They also explored the robustness of the PrinTracker on objects with different geometric shapes, where the precision and recall dropped to 83% for printed cartridges due to their excessive curvature. While the overall results of these two studies are technically compelling, both approaches largely rely on access to intact, planar surface regions. In forensic casework involving 3DPFs, the availability of such surfaces post-firing may be severely limited due to heat exposure, mechanical deformation, abrasion, and fragmentation. Furthermore, the curvature of components such as barrels may also significantly affect the effectiveness of surface-texture-based attribution methods when applied to 3DPF components.

Alternative approaches include thermal fingerprinting, such as Gao et al.'s (2021) ThermoTag method, which exploits the unique thermodynamic properties of each printer's extruder hot-end. By analyzing heating response curves, ThermoTag can identify printers and even individual hot-ends with circa 92% accuracy, demonstrating robustness over time and environmental changes. However, the process relies on having access to controlled pre-heating data which may prove challenging in a casework environment. Other studies have explored vibration and acoustic signatures for printer identification and anomaly detection (Kumar et al. 2024; Mishra et al. 2023), with high levels of printer attribution accuracy using relatively low-cost sensors. While promising for printer monitoring and security applications, these methods also require contemporaneous data capture during the printing process. They show promise in ensuring improved product quality but currently have limited direct applicability to retrospective forensic analysis of recovered 3DPF components. Interestingly, Bimrose et al. (2025) have developed a method to predict the source of 3D-printed parts using images of the parts scanned on a high-resolution flatbed scanner to train a deep learning model, with a $>98\%$ accuracy. Although it should be noted that in this latter study, four different AM methods were explored (MEX, SLA, Carbon DLS and Multi-Jet Fusion (MJF)), each of which produces characteristic differences in surface texture and topography. As a result, the reported performance varied substantially across technologies: MEX showed the lowest accuracy when only very small areas ($<100\,\mu$m) were analyzed, but it achieved the highest accuracy for larger sampled regions ($>10$ mm). These findings suggest that the method's effectiveness may be limited when applied to post-firing polymer debris from MEX-printed firearms, where deformation, heat damage, and fragmentation could further reduce the availability of sufficiently large or intact surface regions for reliable analysis.

Taken together, these studies demonstrate that printer-specific signatures can be generated and detected under controlled conditions, but they also highlight a significant gap between technical feasibility and realistic forensic implementation for 3DPFs. Much of this research has been driven by the need to regulate illegal 3D-printed products, particularly in response to rising criminal activity involving forgeries and copyright violations, rather than by the evidential constraints of criminal firearm investigations. As a result, the integrity, persistence, and reproducibility of identifying marks transferred from a 3D-printer to functional firearm components remain underexplored. The small number of existing studies generally fall into two categories: MEX printer nozzle deposition marks and base plate contact marks. While current studies demonstrate that printer-dependent features can be generated and discriminated under controlled conditions, the extent to which these features remain reproducible, stable, and forensically interpretable in casework contexts remains largely unvalidated.



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### 3.2.1 | MEX Printer Nozzle Deposition Marks

Any microscopic defects or irregularities in the nozzle of an MEX printer can contribute to deposition striae or characteristic impressions on the surface of 3D printed objects. Similarly, any markings or defects on the base plate of the printer can be transferred directly onto the underside of the print, creating distinctive imprint patterns (Figure 4). Collectively, current foundational research suggests that these could serve as class and potentially individual characteristics.

In their comprehensive preliminary research, and further to Pavlovich's MEX deposition striae theoretical discussion article (Pavlovich 2022), Pavlovich and Garrison (2023) explored the possibility of same-source evaluation of consecutively MEX printed PLA filament pistol frames. They proposed a new category of "deposition striae tool marks", which they identified within Mikrosil casts of nozzle detachment and start points on the trigger guard surface of the frames. Using the quantitative method of Consecutive Matching Striae (CMS) to reduce the degree of subjectivity (Nichols 2003), the authors were able to provisionally demonstrate a common source origin for the consecutively manufactured 3D MEX pistol frames using the same 3D-printer and hot-end nozzle, building on Scott's (2022) "proof of concept" findings. Critically, however, these results also highlight key limitations. Deposition striae were shown to be highly sensitive to nozzle travel orientation, meaning that accurate comparison depends on correct alignment of the 'detachment' and 'start-point' axes. Even minor misalignment could yield inconclusive or false-negative results, including between items known to share a common source. This sensitivity raises important concerns regarding operational reliability, particularly in casework contexts where surfaces may be damaged, deformed, or incomplete. Furthermore, as toolmark-based approaches become more widely recognized, individuals could deliberately modify printer components to reduce or remove characteristic striae, potentially weakening the reliability of this method over time for investigative or attribution purposes. A more likely scenario, however, is not intentional nozzle alteration but post-manufacture finishing. Processes such as sanding a 3DPF surface would almost certainly remove fine surface detail, including manufacturing toolmarks. A detailed understanding of internal geometries and assembly processes will therefore be essential in identifying which components are most likely to preserve these marks.

Rather than focusing on microscopic striae within nozzle drag marks, Clifton et al. (2026) examined the overall shape, reproducibility, and variability of these marks across MEX-printed objects, alongside the impact of the print-bed coordinates used during fabrication. Nozzle drag marks were found on all printed items, confirming their ubiquity; however, the geometry and clarity of these marks varied depending on their position on the object's surface. Differences in drag mark characteristics were established between printers of the same make and model, and attribution to the source printer was achieved with an accuracy of 44%. Critically, they demonstrated that object orientation on the print bed influenced drag-mark transfer, as changes in print-bed position and the number of prints on the bed at any one time potentially modified the deposition characteristics.

While this proof of concept study shows that drag-mark formation is sensitive to positional and process-driven factors, its experimental scope was necessarily limited as only one printer make and model was examined in depth. During the study, the approach shifted from printing a single object to producing four simultaneously in different orientations and locations. The authors acknowledge that generating multiple objects, or placing them in different locations on the build plate, necessarily alters the G-code, which further complicates interpretation. The impact of systematically varying other parameters such as layer height or print speed would also deepen understanding of slicer-dependent or G-code-dependent effects on nozzle marks. As a result, the findings, while informative, highlight the need for more controlled and expansive experiments before variability in drag-mark geometry can be relied upon for robust forensic attribution.

Schaufelbühl's (2025) analysis of manufacturing features highlights that variations in slicer settings, G-code, internal structures, and process parameters can affect the surface signatures of printed components, complicating downstream forensic comparison. Together, these works make clear that printing patterns are not solely inherent "signatures" of a device, but also reflect process-dependent artifacts shaped by user-selected parameters, meaning even small adjustments can significantly alter the resulting toolmarks. As a consequence, any forensic attempt to associate items with a specific printer must account for the variability introduced by slicer settings and print-process decisions, in addition to natural printer-to-printer variation.

Although the foundational studies discussed here show promise, substantial knowledge gaps remain. Further investigation is required into the influence of nozzle material, polymer composition and color, and MEX printer makes and models on 3D-printer attribution. Longevity studies would allow for an understanding of how the nozzle surface changes over time, and blind comparisons of marks from consecutively manufactured nozzles are necessary to evaluate the risk of sub-class characteristics and to strengthen confidence in single-source attribution.

### 3.2.2 | Base Plate Marks

The method of MEX 3D-printing can have significant forensic implications, particularly in relation to the base layer of printed objects. As the melted filament cools and solidifies on the printer's base, or build, plate, it can capture and replicate any imperfections present on the surface, effectively acting as a casting medium. Aronson et al. (2021) explored this phenomenon by examining the base face, or the initial layer, of two PLA cubes and six additional 3D-printed objects, five of which represented the lower outer contour of the "Liberator" pistol barrel. Critically, all objects were printed in the same XY starting position on a glass surface covering the heated base plate. Using "RepliSet-F1" silicone rubber casting compound, comparative casts of the glass surface were taken. The researchers found sufficient detail in the base layers to conclusively associate all printed objects with each other and with the cast of the glass base plate. These findings were supported by Nooijen (2023), who conclusively compared base plate marks on multiple 3D-printed calibration cubes from four different G-codes, printed by four individuals, to casts



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of the base plate of each printer used. This suggests that the base plate can retain and transfer distinctive surface features, offering a potential avenue for forensic linkage.

Taking a novel approach to forensic traceability, Vandenburgh (2025) investigated the presence of base plate marks on the bases of PLA-CF 3D-printed projectiles, which remained partially intact following discharge. These granular impressions, originating from the textured surface of the printer's base plate, were still discernible after firing and offered a potential means of linking a projectile back to the specific plate, and by extension, the printer used in its manufacture. When considered alongside the class and individual rifling characteristics transferred from the firearm barrel, this presents a unique dual attribution scenario: the possibility of associating a single projectile with both the weapon that fired it and the printer that produced it.

However, the study also highlighted limitations. The individual rifling marks observed on the 3D-printed projectiles were faint and inconsistently distributed, particularly at the base, where heat and pressure during firing likely degraded the surface. As a result, the level of detail was insufficient to support conclusive association. These findings underscore the need for further research into material selection, propellant load optimization, and post-processing techniques to enhance the forensic viability of 3D-printed ammunition.

When considered together, the nozzle deposition and base plate mark studies reveal a consistent theme: while MEX 3D printers can transfer potentially distinctive marks to printed components, the evidential value of these features is highly contingent on printer configuration, print parameters, and post-manufacture events. Factors such as slicer settings, starting position, calibration, extrusion temperature, print speed, layer height, base plate condition, and filament composition on the formation and individuality of 3D-printing marks have not been systematically studied. Variations in these parameters may alter the clarity, consistency, and distinctiveness of deposition striae, surface textures, and base plate impressions, potentially affecting their forensic utility. Understanding how these factors shape individual characteristics is essential for developing validated and reliable attribution methods and for assessing the evidentiary value of 3DPFs. This represents a key area for future research, particularly in bridging the gaps between engineering precision, forensic traceability, and judicial scrutiny.

## 3.3 | Residual Trace Polymer Evidence

### 3.3.1 | Detection of Residual Trace Polymer Evidence

Within this section, residual trace polymer evidence refers to minute quantities of polymer that may have been deposited on surfaces or cartridge cases and bullets during the discharge of a 3DPF that are not necessarily visible to the naked eye.

Residual trace polymer evidence from 3DPFs has been identified on bullets, cartridge cases, and surrounding surfaces post-discharge. Collectively, the available studies suggest that polymer transfer is possible, but not inevitable, and that its detectability is highly sensitive to firearm design, cartridge power, printing technology, and analytical method. Importantly, the reviewed literature does not present a uniform picture of residual trace polymer deposition, reflecting substantial variation in experimental design, such as 3DPF model, caliber, printer, filament, and analytical approach. As such, these findings are best interpreted comparatively rather than chronologically and are discussed below and summarized in Table 2.

A clear distinction exists between studies relying primarily on visual observations and those employing chemical or spectroscopic analysis. Some investigations consistently reported the presence of apparent polymer residues on bullets, cartridge cases, and in the vicinity of the discharge event (Honsberger et al. 2019; Trincat et al. 2022; Szwed et al. 2023; Wenzinger et al. 2024). Collectively, these studies suggest that polymer transfer can occur during firing and that residue may be distributed across multiple evidential locations, including projectiles, cartridge cases, firearm components, and the surrounding environment. Furthermore, the recovery of larger polymer fragments and printing-related debris supports the proposition that forensic opportunities may extend beyond traditional ballistic evidence to include residues deposited on a shooter's hands, clothing, or nearby surfaces. However, visual observations alone cannot confirm the identity of transferred material or distinguish relevant polymer residues from environmentally derived plastic contaminants. Consequently, while these studies provide evidence that material transfer is possible, the evidential value of these findings relating to source attribution is limited by the absence of chemical characterization.

Studies incorporating chemical analysis provide stronger evidential support but also reveal variability in residue detection (Adamos et al. 2025, 2026; Black et al. 2017; Crowe and Rugh 2017; Falardeau et al. 2024). These findings indicate that transferred polymer residues can, under certain circumstances, survive discharge and be distinguished from background materials using appropriate analytical techniques. Falardeau et al. (2024) reported no detectable polymer residues on bullets or cartridge cases despite employing FTIR and Raman spectroscopy and constructing a comprehensive spectral reference database. This finding contrasts directly with the findings of Black et al. (2017) and highlights one of the key challenges in interpreting the current literature. While methodological differences may partially explain this discrepancy, firearm design appears particularly significant. Unlike studies examining fully printed firearms, Falardeau et al. investigated only 3D-printed barrels mounted onto a commercial receiver system. This raises an important question regarding which components of a 3DPF contribute most significantly to the deposition of residual trace polymer evidence. This divergence strongly suggests that polymer deposition is not solely dependent on barrel material but may instead arise from interactions among multiple printed components, particularly the chamber, breech, and receiver structures present in fully printed firearms.

An additional limitation affecting forensic interpretation is the current inability to attribute recovered polymer residues to a specific printer, manufacturer, or user. Adamos et al. (2025, 2026) demonstrated that FTIR could reliably differentiate major



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**TABLE 2** | Comparative review of studies on polymer trace evidence and analytical findings in 3D printed firearms.

| Study | 3DPF or 3DPF component printed | Number, caliber and method of items printed | Filament used | Printer make and model | Sample type for observation/analysis | Analytical method | Main findings |
|---|---|---|---|---|---|---|---|
| Honsberger et al. (2019) | Liberator | 6 by MEX (5 × 380 Auto, 1 × 25 Auto) | ABS M30 | Fortus 400mc | Bullets, cartridge cases, environment | Visual, Polilight PL500 | • Polymer on bullets and cartridge cases<br>• Target substance affected the form of polymer on bullets (melted/flaked)<br>• Distal larger polymer fragments up to 9 m<br>• No characteristic marks on bullets<br>• Toolmarks in firing pin impression<br>• Cartridge cases deformed or ruptured |
| Trincat et al. (2022) | Liberator | 36 × 380 Auto (15 by MEX across two models of printer, 18 by SLA, 3 by SLS) | ABS, PLA, PETG | MEX: Zortrax M200 and Stratasys Fortus<br>SLA: Formlabs Form2<br>SLS: EOSINT P395 | Bullets, cartridge cases, environment | Visual, Polilight PL500 | • SLA 3DPFs non-functioning<br>• Polymer on bullets and cartridge cases, but less on cases compared with bullets<br>• More trace polymer on cases from MEX vs. SLS and ABS in particular.<br>• Distal larger polymer fragments, distance unknown<br>• Printing method and parameters from larger fragments could be identified<br>• No characteristic marks on bullets<br>• Toolmarks in firing pin impression<br>• Cartridge cases deformed or ruptured |
| Brinsko-Beckert and Palenik (2020) | None | | PLA, ABS | 16 MEX printers, various makes and models | Filament dust from printers, raw filament, extruded waste filament | Polarized light microscopy, UV fluorescence microscopy, FTIR, Raman, FE-SEM/EDS, py-GC/MS | • No difference between raw and printed filament<br>• ABS and PLA particles identified in the dust<br>• Inter-variability identified<br>• Fluorescence of ABS limited to thin outer layer of filament<br>• PLA dust particles smaller than ABS and not suitable for FTIR. FE-SEM/EDS and py-GC/MS used for identification and analysis |

(Continues)



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**TABLE 2** | (Continued)

| Study | 3DPF or 3DPF component printed | Number, caliber and method of items printed | Filament used | Printer make and model | Sample type for observation/analysis | Analytical method | Main findings |
|---|---|---|---|---|---|---|---|
| Szwed et al. (2023) | PM422 Songbird, PM522 Washbear, TREVOR, TESSA, Marvel Revolver, Grizzly | 1 of each by MEX .22LR: Songbird, Washbear, Trevor, Grizzly 9mmP: TESSA 38 SpL: Marvel | PLA | Prusa i3 MK3S | Bullets, cartridge cases, environment | Visual, Polilight PL500 | • Distal smaller polymer fragments from all, distance unknown<br>• Polymer on bullets and cartridge cases, more on 9 mmP and 38 Spl bullets<br>• Less polymer on cases compared with Honsberger et al. (2019)<br>• Cartridge cases deformed or ruptured |
| Wenzinger et al. (2024) | Liberator | 1 body and 10 barrels printed (380 Auto) | Body: PLA Hammer: ABS Barrels: ABS (×3), Nylon (×5), PLA (×2) | Creality Ender 3 | Bullet, cartridge cases, GSR samples, environment | Visual | • Only one PLA barrel used due to destruction of rest of pistol.<br>• Blue/green mark found on bullet<br>• No characteristic marks found on bullet or cartridge case |
| Crowe and Rugh (2017) | Not known | 5 (.22LR and 380 Auto) | ABS | Not known | SEM stubs, muzzle wipes | GSR: SEM/EDS Polymer: IR micro-spectroscopy | • ABS polymer on SEM stubs and muzzle wipes<br>• Unusual GSR particle shape, indicating fusion of polymer trace and primer residues |
| Black et al. (2017) | Phase 1: Crude firearm Phase 2: PM522 Washbear | Phase 1: MEX (38Spl) Phase 2: MEX (.22LR) | Phase 1: ABS and Nylon barrel Phase 2: PLA except cylinders. Four cylinders in ABS, PLA, PETG and CPE | Ultimaker 2+ | Bullet, cartridge cases, SEM stubs, common 3D-print polymers | DART-MS, SEM/EDS, DSC | Phase 1:<br>• ABS/Nylon and OGSR on cartridge case<br>• ABS on bullet<br>• OGSR on SEM stub<br>Phase 2:<br>• ABS/PLA/PETG/CPE and OGSR on cartridge case<br>• ABS/PLA on bullet (not PETG/CPE)<br>• ABS/PLA/PETG/CPE on SEM stub<br>• OGSR and nitroglycerine on SEM stub<br>• SEM confirmed IGSR, but couldn't distinguish OGSR from polymer<br>• DSC distinguished polymers |

(Continues)



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**TABLE 2** | (Continued)

| Study | 3DPF or 3DPF component printed | Number, caliber and method of items printed | Filament used | Printer make and model | Sample type for observation/analysis | Analytical method | Main findings |
|---|---|---|---|---|---|---|---|
| Falardeau et al. (2024) | Barrels only (fitted to Ruger 10/22 rifle receiver) | 8 barrels by MEX (.22LR) | ABS, Nylon-CF, PC CPE (×2), PETG-CF, PLA, Value PLA, TPU | Creality CR-10s Pro | Pre and post printing polymer, Bullets, cartridge cases, environment | ATR-FTIR, Raman, chemometric analysis | • Reference polymer spectral database created<br>• Low intra-, high inter-variability<br>• No polymer traces on bullets or cartridge cases<br>• Distal smaller polymer fragments from all, 0–2 m<br>• Spectral variation between printed and non-printed filament, more with FTIR |
| Adamos et al. (2026) | None | 27 non-firearm related objects by MEX | PLA, ABS, PETG plus enhanced blends incl. PLA$^{+}$, PETG-CF, PLA-CF | Unknown All printed samples either purchased or donated | Pre and post printing polymer, 1.9 cm printed discs, or "filament color swatches" from Bambu-Lab | ATR-FTIR, chemometric analysis | • Filament identification achieved for each polymer category<br>• Low intra-, high inter-variability<br>• Outer layer coating identified on filaments<br>• Surface vs. core chemical differences demonstrated in printed objects |

Abbreviations: ATR-FTIR, Attenuated Total Reflection Fourier-Transform Infrared spectroscopy; DSC, Differential Scanning Calorimetry; FE SEM/EDS, (Field Emission) Scanning Electron Microscopy-Energy Dispersive Spectroscopy; MEX, Material Extrusion; Py-GC/MS, pyrolysis Gas Chromatography/Mass Spectrometry.



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polymer classes and identify subgroups but could not associate material with particular suppliers. Furthermore, the observation that printed objects may possess chemically distinct surface and core compositions highlights an important sampling consideration. Comparisons between filament, printed objects, and recovered residue may therefore be influenced by sampling location and depth, potentially leading to misleading conclusions regarding source attribution.

In summary, the analytical approaches used in the literature discussed here differ substantially in sensitivity and forensic applicability. Visual examination can identify macroscopic fragments but provides no chemical specificity. Spectroscopic methods such as FTIR and Raman spectroscopy offer rapid and non-destructive polymer identification but may be limited by the quantity and condition of recovered material. Mass spectrometric approaches, including DART-MS and py-GC/MS, provide greater chemical discrimination but often require more specialized instrumentation and analytical expertise. Consequently, apparent disagreements between studies may reflect differences in detection capability as much as genuine differences in residue generation.

#### 3.3.2 | Residual Trace Polymer Future Directions

Taken together, these studies indicate that the deposition of residual trace polymer evidence from 3DPFs is context-dependent rather than ubiquitous. Polymer transfer appears most likely when firearms are fully printed, chamber integrity is poor, and higher-powered cartridges are used. Partially printed hybrid designs may substantially reduce or eliminate detectable polymer deposition because metal components are frequently used for pressure-bearing regions, thereby limiting the direct contact between the ammunition components and printed polymer surfaces. Differences in analytical methodology further compound interpretive variability. Future research should therefore focus on systematically isolating and testing individual 3DPF components, such as barrels, chambers, hammers, and receivers, fabricated from different polymers to determine their respective contributions to residual trace deposition. Controlled firing experiments using varied cartridge loads and environmental conditions could help establish thresholds for polymer transfer. Dispersal studies on residual trace polymer deposition could be undertaken to evaluate parameters influencing transfer to a shooter's hands and clothing. Complementary chemical analyses of these residues may also identify environmental contaminants or interactions with cartridge components, propellants, and primers. Additionally, expanding spectroscopic analysis to include emerging polymer blends and additives used in hobbyist and industrial 3D-printing would enhance forensic traceability.

Furthermore, the findings outlined above suggest that polymer analysis alone is currently unlikely to provide specific 3D-printer attribution. This highlights the importance of a collaborative approach across diverse forensic disciplines, including toolmark comparison, residual trace polymer analysis, GSR examination, 3D-printer deposition striae analysis, as well as digital forensics, not only within individual cases but also between cases. By integrating findings across these domains and systematically recording them via casework strategy reporting frameworks within shared databases or intelligence frameworks, similarities in materials, manufacturing artifacts, or printer-specific characteristics can be identified across separate incidents. Such an approach enables the potential linking or exclusion of cases involving the same printer or printing practices, thereby increasing the likelihood of meaningful attribution, robust elimination, and investigative linkage over time.

Research into the parameters influencing the functionality and structural integrity of 3D-printed objects, such as polymer filament properties, deposition quality, and microstructural characteristics, is well established (Arunprasath et al. 2022; Chacón et al. 2017; El Moumen et al. 2019; Khosravani et al. 2022; Kuleyin et al. 2025; Ngo et al. 2018; Soares et al. 2018; Tymrak et al. 2014). However, these studies fall outside the specific forensic context of 3DPFs.

In forensic investigations, the mechanical reliability of a 3DPF is not merely a matter of engineering; it can be critical to understanding the weapon's viability and evidentiary value. Factors such as polymer deposition consistency, internal microstructure, and tensile strength could directly influence whether a printed firearm can withstand the pressures of discharge or whether it may catastrophically fail. Such failures could have implications for both user safety and forensic interpretation, particularly in cases involving attempted use or suspected criminal intent.

Moreover, does the forensic principle underpinning toolmark examination, that manufacturing processes leave unique, reproducible marks, extend to 3D-printing? The layer-by-layer deposition process in MEX printing, nozzle wear, filament feed rate, and thermal settings could all contribute to distinctive striae, surface textures, and micro-artifacts on printed components. These features may serve as individual characteristics, potentially linking a printed firearm or its parts to a specific printer or filament batch. However, the extent to which these features are influenced by variations in printing parameters, such as temperature, speed, infill density, and filament composition, remains underexplored in the forensic 3DPF context.

Altering these parameters could significantly affect the formation, clarity, and consistency of deposition striae and other microscopic features, potentially enhancing or obscuring their evidentiary value. For example, a change in nozzle temperature might alter polymer flow and surface finish, while filament additives or pigments could impact spectral signatures used in chemical analysis. Understanding these effects is crucial for developing robust forensic comparison methodologies and for assessing the reliability of linking evidence to a specific printer or user.

This gap in research highlights the need for systematic forensic studies that investigate how 3D-printing variables influence the individuality and reproducibility of residual trace polymer features. Such work would not only strengthen the evidentiary basis for 3DPF investigations but also support the development of standardized protocols for forensic comparison and attribution.



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### 3.4 | Gunshot Residues (GSR)

Traditional GSR is typically categorized into inorganic GSR (IGSR), derived primarily from primer components (e.g., lead, barium, antimony), and organic GSR (OGSR), originating from propellants and their additives. In the context of 3DPFs, GSR must be interpreted more broadly than in conventional firearms analysis due to the additional presence of polymer residues, also discharged from the muzzle of the firearm upon firing. When polymer material is thermally altered, fragmented, or fused with primer or propellant residues during discharge, it may form chemically and morphologically distinct hybrid particles that are intrinsically linked to the firing event. This distinction was first intimated by Crowe and Rugh (2017), who demonstrated that GSR had been recovered and identified following the test firing of five 3DPFs. Using SEM/EDS, they found that some GSR particles deviated from classical spheroidal IGSR and exhibited atypical shapes, suggesting a fusion of polymer and primer residues, indicating that discharges from polymer firearms may produce hybrid residues with distinct morphological features not commonly seen in conventional firearms. These observations imply that polymer present within the discharge environment may not merely coexist with GSR but become incorporated into it, producing composite residues that are forensically meaningful. Importantly, such fused particles cannot be considered equivalent to unassociated residual trace polymer, as their formation appears contingent on the high-temperature, high-pressure conditions of firing.

In contrast, Black et al. (2017) employed DART-MS, alongside SEM/EDS, to examine GSR from the two types of 3D-printed firearms discussed in Section 3.2.1 above. DART-MS successfully identified both polymer residues and OGSR compounds, such as ethyl centralite, methyl centralite, diphenylamine, and nitrocellulose, on bullets, cartridge cases, and GSR stubs. However, their findings also highlighted a significant analytical limitation: SEM/EDS could not reliably distinguish between OGSR and polymer fragments due to their shared organic composition and overlapping particle morphologies. This limitation becomes particularly problematic when polymer has been chemically or physically altered during firing, as such material is no longer simply "polymer debris" but part of a complex residue assemblage. The study therefore underscores the need for complementary analytical techniques in 3DPF-related forensic investigations to avoid misclassification and to properly attribute polymeric material to a firing-related origin rather than an environmental source. Subsequent investigation by Black and Cizdziel (2019) focused on assessing the maximum distance at which polymers can be detected in GSR produced by a 3DPF, again using DART-MS and validated across several laboratories; however, the results do not appear to have yet been published.

Although Trincat et al. (2022) and Szwed et al. (2023) successfully identified unburnt and partially burnt propellant flakes following the test firing of various 3DPF models across multiple polymer compositions, their analyses remained limited to conventional microscopy. They did not further investigate the chemical composition or morphological characteristics of any microscopic primer-based IGSR or propellant-based OGSR that may have been present.

Despite growing interest in the forensic implications of 3DPFs, the examination of GSR within this context remains notably underexplored. To date, there is an absence of published research specifically addressing how the materials, construction methods, and firing mechanisms of 3DPFs may influence the generation, composition, and dispersal of GSR. This is a critical gap, as GSR analysis is integral to conventional firearm investigations, often used to determine firing events, shooter proximity, and aid in the identification of weapon and ammunition types.

Black and Cizdziel (2019) proposed that utilizing scanning analytical techniques such as FTIR and Raman spectroscopy enables the acquisition of spectroscopic data from multiple locations within a sample. This approach could help construct a detailed narrative of the firing range and deposition profile of both GSR and residual trace polymers present within the discharge plume. This may enable discrimination between polymer that is merely present in minute amounts and polymer that has undergone physicochemical modification consistent with discharge, thereby supporting the identification of polymer–GSR hybrids as firing-related residues.

The absence of empirical data raises important research questions within this context: Do polymer-based barrels alter the thermal or chemical profile of GSR? Could the use of hybrid components (e.g., metal firing pins or barrels/chambers) produce residues consistent with traditional firearms, or introduce novel particulate signatures? Furthermore, the potential for incomplete combustion or altered pressure dynamics in 3DPFs may affect the quantity and distribution of GSR-polymer hybrids, complicating interpretation. Addressing these questions through controlled experimental studies is essential to ensure that forensic protocols remain robust and adaptable in the face of emerging firearm technologies.

### 3.5 | Firearms Identification

In practice, the type of barrel present in a 3DPF varies substantially by construction method. F3DPFs often incorporate polymer barrels that may lack defined rifling or exhibit rapidly degrading internal features, whereas hybrid designs may employ inserted smooth-bore metal tubes or electrochemically machined (ECM) barrels capable of imparting more consistent rifling marks. More recently, the advent of metal AM has enabled the production of barrels in which rifling is incorporated as an inherent feature of the printing process rather than introduced through conventional manufacturing methods such as button, cut, broach, or hammer forging rifling. In contrast, parts-kit completions typically use conventionally manufactured barrels, resulting in toolmarks and rifling characteristics broadly comparable to those observed in traditional firearms. Collectively, this has implications for the production and reproducibility of firing marks. The forensic examination of 3DPFs, particularly those constructed from polymer-based materials, presents unique challenges. Unlike conventional firearms, polymer barrels often fail to impart rifling marks or distinctive toolmarks on bullets and cartridge cases, thereby limiting the effectiveness of traditional forensic identification techniques. Limited studies have explored the identification and comparison of firing marks on bullets and cartridge cases fired in 3DPFs. However, as similarly outlined in Section 3.3.1, significant differences in experimental design complicate the comparison of findings, which are discussed below and summarized in Table 3.



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**TABLE 3** | Comparative summary of studies on mark formation and source attribution in 3D printed firearms (F3DPF = Fully 3D Printed Firearm, FRP = Fiber Reinforced Plastic).

| Study | 3DPF or 3DPF component printed | 3DPF design, including bore profile | Number, caliber and method of items printed | Filament/ print substrate used | Printer make and model | Number of shots fired | Comparison possible/ performed? | Main findings |
|---|---|---|---|---|---|---|---|---|
| Wenzinger et al. (2024) | Liberator | F3DPF (smooth bore) | 1 body and 10 barrels printed (380 Auto) | Body: PLA<br>Hammer: ABS<br>Barrels: ABS (×3), Nylon (×5), PLA (×2) | Creality Ender 3 | 1 | No | • Only one PLA barrel used due to destruction of rest of pistol.<br>• No characteristic marks found on bullet or cartridge case<br>• Primer blow out |
| Honsberger et al. (2018, 2019) | Liberator | F3DPF (smooth bore) | 6 by MEX (5 × 380 Auto, 1 × 25 Auto) | ABS M30 | Fortus 400mc | 1 from each 3DPF | No | • No characteristic marks on bullets<br>• Toolmarks in firing pin impression<br>• Cartridge cases deformed or ruptured<br>• Some features of headstamp on hammer body |
| Trincat et al. (2022) | Liberator | F3DPF (smooth bore) | 36 × 380 Auto (15 by MEX across two models of printer, 18 by SLA, 3 by SLS) | ABS, PLA, PETG | MEX: Zortrax M200 and Stratasys Fortus<br>SLA: Formlabs Form2<br>SLS: EOSINT P395 | 1 from each functioning 3DPF | No | • SLA 3DPFs non-functioning<br>• No characteristic marks on bullets<br>• Toolmarks in firing pin impression<br>• Cartridge cases deformed or ruptured<br>• No evidence of headstamp on hammer body |

(Continues)



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**TABLE 3** | (Continued)

| Study | 3DPF or 3DPF component printed | 3DPF design, including bore profile | Number, caliber and method of items printed | Filament/ print substrate used | Printer make and model | Number of shots fired | Comparison possible/ performed? | Main findings |
|---|---|---|---|---|---|---|---|---|
| AlShamsi (2019) | Liberator | F3DPF (smooth bore) | 1 by MEX (.32–20 Winchester), plus two replacements barrels | ABS and ABS/FRP | Felix PRO 2 | 1 from original Liberator; 2 from original body fitted with replacement barrel | Yes (cartridge cases only) | • Barrel of first Liberator failed after firing, reprinted in ABS/FRP for second firing.<br>• No characteristic marks on bullets<br>• Firing pin drag marks support same source identification<br>• Sufficient agreement found between test marks from nail in isolation and fired cartridge cases |
| De Schutter and Heymans (2025) | Yeet22 | Hybrid (smooth bore) with sound moderator | Not identified (.22 Long Rifle) | Not identified | Not known. Item submitted for forensic examination | 40 | Yes | • No characteristic marks in firing pin impression<br>• Characteristic rim mark on all cartridge cases<br>• Chamber marks support same source identification<br>• Characteristic marks on bullets from sound moderator, marks degraded over time<br>• Bullets from shots 1–2 could be microscopically associated<br>• By 15th shot, suppressor mark had changed and couldn't be associated with bullets 1 and 2 |

(Continues)



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**TABLE 3** | (Continued)

| Study | 3DPF or 3DPF component printed | 3DPF design, including bore profile | Number, caliber and method of items printed | Filament/ print substrate used | Printer make and model | Number of shots fired | Comparison possible/ performed? | Main findings |
|---|---|---|---|---|---|---|---|---|
| Li et al. (2021) | Colt 1911 Mk IV/Series '70 Government Model (Barrel only) | Metal (rifled, as printed) | 2 by SLS (45 Auto) | INCONEL metal alloy 718 | Not identified | 100 per barrel | Yes | • Rifling characteristics unique to each barrel identified<br>• Rifling marks in land impressions support same source identification across all 100 bullets in each barrel<br>• Striations on earlier bullets more pronounced<br>• Significant disagreement between bullets fired in each barrel; elimination achieved |

Wenzinger et al. (2024) investigated the ballistic signatures of the "Liberator" 3D-printed pistol and observed firing marks on both bullets and cartridge cases. However, they were unable to identify any useful individual characteristics, likely due to the use of PLA, nylon, and ABS materials for the barrels, which may lack the hardness and consistency required to produce reproducible microscopic markings. These findings supported those of Honsberger et al. (2018, 2019). However, in these earlier studies, marks in the firing pin were excluded from the scope of the research as they were identified as not being specific to the Liberator. Whilst the firing pin had not been 3D-printed, and was instead a modified simple nail, it is the first author's extensive casework experience that marks within the improvized firing pins of modified firearms have been a rich source of distinctive characteristics, supporting same source association. Trincat et al. (2022), also found no useful firing marks attributable to 3D-printed components on bullets fired from Liberator pistols, but did acknowledge that marks within the firing pin impression on cartridge cases may be useful for comparison purposes. This was demonstrated by AlShamsi (2019), who reported sufficient agreement in firing pin drag marks to support same source association, concluding that a recovered cartridge case had been fired from an ABS/Fiber Reinforced Plastic (FRP) "Liberator" pistol. Notably, all studies involved a small number of test firings and did not explore blind testing protocols. These constraints were largely due to the frangible nature of the "Liberator" design, which restricts repeated use and consistent ballistic performance.

A critical factor in these findings is the firing pin itself, which in many 3DPFs is not 3D-printed but instead fashioned from conventional metallic components, such as hardware nails. This introduces a variable that may produce toolmarks similar to those found in traditional firearms and converted blank-firing pistols. However, the mismatch in chamber pressures and mechanical tolerances between the printed components and the metallic firing pin could influence how the pin interacts with the cartridge case, potentially affecting the reproducibility and clarity of the marks.

De Schutter and Heymans (2025) conducted ballistic testing on a 3DPF resembling the "Yeet22" pistol, which was one of only two 3DPFs submitted to the Belgian National Institute of Criminalistics and Criminology at the time of their study. The firearm featured a metal firing pin and an unrifled metal barrel, along with a 3D-printed sound moderator. Although the specific polymers used in the construction were not analyzed, the hybrid design allowed for a more extensive test series than previous studies, with 40 shots successfully fired. Unlike earlier research, which was limited by the fragility of polymer barrels, this study found that while the firing pin impressions lacked individual characteristics, chamber marks on the cartridge cases were sufficiently distinctive to allow single-source attribution, most likely due to the metallic composition of the chamber. Additionally, the sound moderator was found to shear the bullets, producing characteristic, observable striations. However, these striae degraded over time. While the first bullets could be positively associated, by the 15th shot, the markings had changed significantly, rendering further comparisons unreliable.



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In contrast to earlier studies focused on polymer-based 3DPFs, Li et al. (2021) examined firing marks produced by two consecutively manufactured rifled barrels made from INCONEL metal alloy using SLS technology. This approach allowed for significantly greater durability, enabling 100 rounds to be fired through each barrel, far exceeding the firing capacity of polymer-based designs. Despite the absence of traditional tooling on the inner surfaces of the barrels, the researchers were able to distinguish between bullets fired from each barrel. This differentiation was attributed to minute dimensional variations inherent in the SLS manufacturing process (Scott 2019). Furthermore, intra-barrel comparisons revealed a high degree of consistency: the 100th bullet could be conclusively matched to the 1st bullet fired from the same barrel. However, it was noted that the striations on the earlier bullets were more pronounced than those on later rounds, suggesting progressive wear or surface smoothing over time. As proposed by Day (2020), broader validation across different alloys and AM methods is needed. Nonetheless, this study demonstrates the potential for high-resolution AM to produce barrels capable of generating reproducible, characteristic ballistic signatures, even in the absence of conventional machining.

Hybrid 3DPFs, which incorporate both polymer and metallic components, present a complex forensic landscape. The inclusion of metal parts, such as barrels, chambers, or firing pins, can enhance the reproducibility of firing marks, particularly bore marks, chamber marks, and firing pin impressions. However, the evolving wear patterns of 3D-printed polymer components, especially sound moderators and barrels, introduce significant challenges for long-term ballistic comparison. Moreover, current literature lacks detailed consideration of class and subclass characteristics within the firing marks observed in hybrid 3DPFs. This omission restricts the ability to distinguish between marks that are distinctive to a specific firearm and those that may be common across multiple units produced using similar methods, equipment, or materials. The influence of polymer deposition methods, such as MEX, SLA, or SLS, on the integrity and reproducibility of firing marks also remains largely unexplored in forensic literature. Similarly, the impact of polymer type on surface texture, dimensional stability, and the transfer of microscopic markings to fired ammunition is seldom addressed. These factors are critical, as variations in printing technique and material composition are likely to affect the formation and consistency of toolmarks, potentially altering the evidentiary value of recovered bullets and cartridge cases.

Understanding the interplay between material properties, manufacturing techniques, and ballistic performance is essential for developing robust forensic protocols. As hybrid 3DPFs become more prevalent, future research must address these gaps through controlled, blind testing and comprehensive documentation of both firearm construction and ballistic outcomes.

## 4 | Quantitative Analysis in 3D-Printed Firearm Identification

Historically, and currently, firearm toolmark examination reporting in the UK has been subjective, based on a five-point conclusion scale, with each comparison undergoing peer-reviewed quality assurance:

1. Match: Samples were fired in the same weapon.
2. Indications of a match: Samples may have been fired in the same weapon, but similar weapons cannot be ruled out.
3. Inconclusive: No determination can be made.
4. Indications of no match: Samples were likely fired from different weapons, though a match cannot be ruled out.
5. No match: Samples were not fired in the same weapon.

Similarly, the majority of examiners in the USA follow the Association of Firearm and Toolmark Examiners (AFTE) Theory of Identification for qualitative conclusion scale and a four-stage examination process, including peer verification (AFTE 2013). While these approaches have been applied successfully to conventionally manufactured firearms, their direct transferability to 3DPFs remains uncertain due to the fundamentally different manufacturing processes and resultant toolmark characteristics.

The 2009 National Academy of Science (NAS) report highlighted the subjective nature of toolmark comparisons, noting that decisions rely heavily on examiner expertise and lack statistical foundations (National Research Council 2009). These limitations are further amplified in the context of 3DPFs, where examiner familiarity with class and individual characteristics may be limited and where the variability introduced by AM processes challenges traditional pattern recognition approaches. In response to the NAS report, there have been several research projects assessing the validity and reliability of forensic firearms examiners (Bolton-King 2016; Hamby et al. 2009; Mattijssen, Witteman, Berger, Brand, and Stoel 2020; Mattijssen, Witteman, Berger, and Stoel 2020; Monson et al. 2022; Scurich et al. 2022). Furthermore, these studies have overwhelmingly focused on metal, factory-produced firearms, rather than polymer-based or hybrid systems. Despite advances in imaging, such as 3D systems and Virtual Comparison Microscopy (VCM) platforms, casework firearm identification conclusions currently remain qualitative within the UK (Chapnick et al. 2021; Duez et al. 2018). The reliance on subjective interpretation is especially problematic in the context of 3DPFs. Firing marks produced by these weapons may differ substantially in morphology, reproducibility and temporal stability compared with those produced by conventionally manufactured firearms. For example, the layered manufacturing processes inherent to AM may produce toolmarks that are less consistent and more difficult to characterize. Furthermore, the materials commonly used in 3D printing may deform, wear, or degrade more rapidly than traditional metallic components, potentially altering the appearance of firing marks over relatively short periods of use. Furthermore, the number of such firearms submitted for examination remains comparatively low, resulting in a restricted body of reference material and limited opportunities for examiners to develop familiarity with their characteristic mark patterns. Consequently, practitioners are likely to encounter these marks far less frequently than those produced by conventional firearms, reducing both experiential knowledge and the ability to reach consensus regarding their interpretation.



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Biasotti and Murdock (1997) developed quantitative Consecutive Matching Striae (CMS) identification criteria, which was an attempt to numerically describe the observed pattern within the traditional pattern matching approach of firearms identification (Nichols 2003). Whilst it has not, as yet, been incorporated into the AFTE Theory of Identification, it is a useful starting place to introduce objectivity into firearms identification practice. The layered nature of MEX printing, printer-specific artifacts, and post-printing finishing may produce distinctive, non-traditional striation patterns that do not align neatly with classical CMS assumptions, highlighting the need to reassess such criteria for printed firearms.

In the UK, the Forensic Science Regulator (2021) has mandated a shift towards objective, likelihood ratio-based evaluations within a Case Assessment and Interpretation (CAI) framework by October 2026. Over recent years, there have been several publications exploring the quantitative imaging and measurement of firearm toolmarks using promising methodology such as micro-computed tomography (micro-CT) and geometric measurement (Alsop et al. 2021; Senin et al. 2006). Likelihood ratios have been calculated for firing marks on cartridge cases, often based upon the Congruent Matching Cells (CMC) method (Basu et al. 2022; Mattijssen, Witteman, Berger, Brand, and Stoel 2020; Riva et al. 2020; Song et al. 2020). Whilst this research makes great strides towards developing a CAI evaluative reporting approach to firearms identification, further studies are needed to include projectiles, and a variety of types and calibers of firearms, including 3DPFs and the converted blank-firing weapons commonly encountered in UK casework. These categories of non-conventional firearms often exhibit atypical firing pin designs, printed breech faces, modified or improvised barrels, or modular and replaceable components, all of which may influence the formation, persistence and individuality of toolmarks.

The absence of published research on the quantitative analysis of firing marks produced by 3DPFs and converted blank-firing weapons presents a pressing challenge. These weapons often exhibit non-standard manufacturing characteristics, such as variable surface finishes, inconsistent barrel geometries, and the use of unconventional materials, all of which may affect the reproducibility and distinctiveness of toolmarks. Additionally, the rapid evolution of 3DPF designs, printers, and printing materials introduces further complexity in establishing reliable identification criteria.

To support the transition to more objective, likelihood ratio-based reporting, it is essential to develop validated methodologies capable of handling the unique features of 3DPFs. However, before quantitative approaches can be robustly implemented, a more fundamental understanding of the nature of residual traces and toolmarks associated with these firearms is required, alongside a critical evaluation of the evidential value of different types of examinations. While existing studies demonstrate clear potential in this area, they also highlight that significant foundational work is still needed. As such, methodological development should proceed in parallel with efforts to better characterize these toolmarks, with careful consideration given not only to how they are analyzed, but also how they are deposited and how the resulting findings are interpreted within this context. Key areas for development include:

- Establishing reference databases of 3DPF toolmarks across different designs and materials.
- Evaluating the performance of imaging techniques (e.g., micro-CT, VCM) in capturing, comparing and evaluating 3DPF marks, alongside emerging approaches such as deep learning. Assessing the error rates and discriminative power of quantitative comparison methods when applied to 3DPFs.
- Investigating the impact of post-processing techniques (e.g., polishing, rifling inserts) on toolmark formation.

While deep learning offers potential for automating feature extraction and improving pattern recognition, its application in this domain remains at an early stage. Current limitations include the need for large, high-quality labeled datasets, challenges around model interpretability and transparency, and a lack of standardized validation frameworks. As such, its use should be considered exploratory and supplementary until robust validation studies demonstrate reliability and reproducibility in forensic contexts.

Without the research summarized above, forensic practitioners risk applying methodologies developed for conventional firearms to 3DPFs without adequate validation. This may undermine the robustness and transparency of evaluative opinions presented in court, particularly in a regulatory environment that increasingly demands demonstrable objectivity and evidential reliability.

## 5 | Future Research

To address the challenges outlined in this review, future research should prioritize:

- Validation of forensic attribution techniques, including blind testing of deposition striae and base plate marks across diverse printer models, nozzle compositions, and filament types. This should also include longevity studies to determine how deposition striae change over time and, most importantly, comparisons of consecutively manufactured nozzles to exclude the influence of sub-class characteristics.
- Controlled firing experiments to assess the impact of cartridge load, environmental conditions, and component composition on residual trace deposition and ballistic signatures.
- Exploration of hybrid firearm dynamics, focusing on the interplay between printed and metallic components in toolmark formation, as well as the generation and deposition of residual trace polymers and GSR.
- Integration of spectroscopic and mass spectrometry methods to enhance residual trace polymer analysis and GSR characterization, including identification and analysis of 3D printer dust and fired residual trace polymer on the shooter.



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- Development of a research-focused database, embedded within a trusted community of 3DPF experts, to track emerging designs, modifications, and manufacturing practices, ensuring forensic research remains aligned with contemporary criminal use rather than legacy demonstrator models.
- Development of quantitative reference databases for toolmarks and residual trace polymer evidence associated with 3DPFs, encompassing a broad spectrum of designs, materials, and printing parameters. This would support the creation of validated 3DPF-specific CAI evaluative reporting frameworks. There is also scope to integrate emerging technologies, such as deep learning, to enhance pattern recognition and classification accuracy.
- Collaboration across forensic disciplines, combining engineering, chemistry, digital forensics, and ballistics to develop comprehensive attribution protocols.
- Policy-oriented studies to evaluate the effectiveness of emerging legislative frameworks and inform evidence-based regulation.

By addressing these areas, the forensic community can better respond to the growing presence of 3DPFs, ensuring that investigative and judicial processes remain scientifically rigorous and legally defensible in the face of technological innovation.

## 6 | Conclusions

This review has highlighted the multifaceted challenges posed by 3DPFs to forensic science, law enforcement, and regulatory frameworks. The rapid evolution of 3DPF technology, coupled with the widespread availability of digital blueprints and consumer-grade printers, has facilitated the proliferation of unregulated and often untraceable weapons. These developments have outpaced existing forensic methodologies and legislative responses, creating a pressing need for targeted research and policy reform. While early studies have necessarily focused on legacy designs such as the Liberator, future forensic research must remain responsive to contemporary criminal practice by aligning academic enquiry with intelligence-led monitoring of emerging 3DPF designs, their modification, and modes of manufacture, supported by secure and trusted information-sharing pathways that enable research to evolve alongside the field.

From a forensic perspective, the identification and attribution of 3DPFs remain complex due to the variability in materials, manufacturing processes, and design modifications. Traditional ballistic comparison techniques are often ineffective when applied to polymer-based firearms, which may lack rifling or consistent toolmarks. Emerging 3D-printer manufacturing evidence, such as deposition striae analysis and base plate mark comparison, alongside residual trace polymer detection, offers promising avenues for source attribution but requires further exploration and validation. The review also underscores the importance of understanding how printing parameters, filament composition, nozzle composition, and post-processing techniques influence the formation and reproducibility of forensic features.

This review also reveals significant gaps in the analysis of GSR and polymer transfer, particularly in hybrid firearms that combine printed and metallic components. These gaps hinder the ability to establish reliable, cohesive forensic linkages between discharged ammunition, the weapon, and the printer of origin. Furthermore, the lack of standardized reporting frameworks and comprehensive seizure data limits the understanding of 3DPF prevalence and criminal use, both domestically and internationally.

Quantitative approaches such as micro-CT imaging, geometric measurement, and likelihood ratio-based evaluations have demonstrated significant potential in conventional firearm identification. However, their application to 3DPFs remains in its early stages. The distinctive material properties, manufacturing variability, and often non-standardized designs of 3DPFs present challenges that conventional methods were not designed to address. As the UK continues its gradual transition to a CAI evaluative reporting model, there is a pressing need to develop robust, objective methodologies tailored specifically to the forensic analysis of 3DPFs. These methodologies must be capable of producing repeatable, validated results that support reliable attribution or elimination, even in the absence of traditional firearm characteristics. The overarching goal is to preserve the scientific integrity of forensic firearm examination, but not necessarily its equipment traditions, by embracing innovation and adapting to emerging technologies. This shift calls for interdisciplinary collaboration, investment in research, and the establishment of new standards that reflect the evolving landscape of firearm-related crime.

As the number of seizures involving 3DPFs continues to rise, it is reasonable to anticipate a corresponding increase in shots fired incidents involving these weapons, particularly as the technology evolves and the firearms themselves become more durable, reliable, and appealing as alternatives to converted blank-firing weapons or OLP firearms. The firing marks left by 3DPFs are often unconventional, potentially resembling those produced by some types of converted blank-firing weapons. In cases where the causative firearm is not recovered, and it is not immediately apparent that a 3DPF was used, the absence of a coordinated, multidisciplinary forensic approach to toolmark and residual trace evidence could result in missed intelligence. This raises a critical research question: Could key indicators of 3DPF involvement have been inadvertently overlooked in past investigations?

### Author Contributions

**Abi Snasdell:** conceptualization, writing – original draft, visualization, writing – review and editing, project administration, methodology, investigation, formal analysis. **Chris Shepherd:** writing – review and editing, supervision. **Bhaven Patel:** writing – review and editing, supervision. **Daniel Sykes:** writing – review and editing, supervision. **Bruno Da Silva Sil Dos Santos:** writing – review and editing, supervision.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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