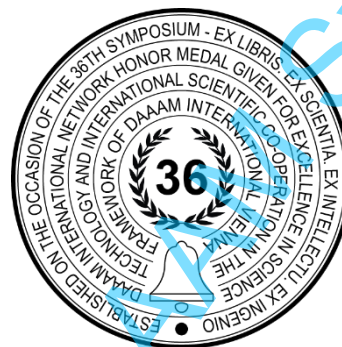


EVALUATION OF FIRING RELIABILITY AND PENETRATION DEPTH OF 3D PRINTED PLA PROJECTILES FOR 9 X 19 MM AMMUNITION

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Abstract

Recent advances in 3D printing technologies and polymer materials have opened new possibilities in various engineering fields, including the defense industry. Among these developments, the concept of 3D printed ammunition has attracted growing attention due to its low cost, rapid prototyping potential, and material flexibility. However, this trend is also raising concerns regarding the reliability, safety, and possible misuse of such ammunition, especially given the limited research available in this domain. In this study, several series of bullet projectiles were produced using an FDM 3D printer with PLA filament, designed according to NATO standards and integrated into live 9×19 mm ammunition. An experiment was conducted to evaluate firing reliability, weapon function, and target penetration behavior using a wooden board as a simplified terminal medium. All shots were successfully fired and analyzed in terms of operational consistency and penetration depth. Based on the experimental results, a preliminary analytical model was developed to support future research and enhance the predictive understanding of such projectiles. The results indicate promising potential for further development of 3D printed ammunition, with practical implications for both research and controlled applications.

Keywords: FDM technology; Ammunition; PLA projectiles; Penetration; Reliability; Ballistics.

1. Introduction

Conventional small-caliber ammunition, which is still the most widely used today, has been manufactured following established technological procedures that have remained almost unchanged for more than a century [1]. Its production does not require highly sophisticated infrastructure, as the machines used to produce projectiles and cases are similar to those used in other metalworking processes. The absence of significant technological barriers for the production of small-caliber ammunition has enabled the development of manufacturing capacities all over the world [1]. Production facilities are capable of mass-producing all components of a cartridge. However, the rapid modernization of the defense industry, the need for mobile production units, the demand for specialized projectiles, and various emergency scenarios have

encouraged the adoption of new, more advanced technologies for the manufacturing of ammunition and even weapons. One of the most notable modern methods is additive manufacturing (AM), particularly 3D printing.

FDM (Fused Deposition Modeling) is the most common 3D printing technique, where thermoplastic material is melted and deposited layer by layer to form a three-dimensional object. Its simplicity, low cost, and wide availability of materials make it suitable for producing various components. In the defense industry, this technology is increasingly used for the rapid fabrication of spare parts, functional prototypes for testing ballistic and mechanical properties, sighting systems, electronics housings, and unmanned aerial vehicle components. FDM printing allows military units to produce critical components directly in the field, reducing logistics and procurement time [2], [3], [4].

According to one of the simplest definitions, a projectile is a body that is launched by an external force and continues its motion due to inertia while being influenced by gravity and air resistance [5]. Therefore, any object that is propelled through the air (or another medium) with an initial velocity caused by an external force—most commonly a weapon system—can be considered a projectile [5]. The primary purpose of a projectile is to damage or destroy a target, making it a key element of ammunition and modern weapon systems [6]. The development of projectiles has a long history, starting with stone, iron, and later lead as materials. Their shapes and materials changed slowly, adapting to various types of weapons such as bows, catapults, cannons, and smoothbore firearms, with significant advancements beginning in the mid-19th century. The most notable progress during this period occurred in the field of small-caliber ammunition and the improvement of the projectiles it uses [7], [8], [9], [10], [11].

In small-caliber ammunition, all elements are often combined into a single unit, which sometimes causes confusion in terminology, particularly with the term “bullet.” For example, a 9×19 mm “bullet” refers to the entire cartridge assembly, which consists of a primer, case, propellant, and projectile. The projectile is only the part that leaves the barrel, often called the “bullet” or “slug.” Since this study deals with designing a polymer projectile for a 9×19 mm cartridge and testing it, it is important to clarify how the system operates. The functioning of a 9×19 mm round involves a precise sequence of events that ensure reliable ignition and energy transfer to the target. After pulling the trigger, the firing pin strikes the primer at the base of the case. The primer ignites the propellant inside the case (typically nitrocellulose in modern ammunition), generating high-pressure gases that push the projectile through the barrel. The projectile then travels toward the target, transferring kinetic energy upon impact.

The most common 9×19 mm projectile is the FMJ (Full Metal Jacket) type, consisting of a lead-antimony core with a copper alloy (tombac) jacket. The material selection is optimized to ensure controlled deformation when hitting hard surfaces, allowing for maximum energy transfer and destructive effect. Since this type of ammunition is primarily designed for use against human targets, the goal is to cause bone fractures (including comminuted fractures that produce multiple fragments, creating dangerous secondary injuries), temporary and permanent cavities in soft tissue, and severe blood loss. If the target is wearing body armor, the projectile still transfers significant energy, causing a strong blunt force impact [12], [13], [14], [15]. The branch of physics that studies the effect of projectiles on targets is called terminal ballistics. Small-caliber projectiles generally do not contain secondary high explosives. Exceptions include pyrotechnic compositions used in tracer rounds.

While conventional ammunition has proven reliable, the ongoing modernization of defense technologies calls for exploring alternatives. Additive manufacturing offers several advantages for ammunition development: fast prototyping, low-cost design iterations, and the potential for lightweight or customized projectiles. It is therefore reasonable to analyze whether 3D-printed projectiles, produced on standard desktop machines using polymers like PLA, can meet the functional requirements of small-caliber ammunition. However, ammunition imposes much stricter demands on reliability, consistency, and safety compared to most other parts, which makes careful testing essential [16].

At the same time, the widespread availability of desktop FDM printers, cheap PLA filament, and free CAD models has significantly lowered the barrier to unregulated or home-made ammunition. This raises security and forensic concerns because such projectiles could work in standard firearms, including “ghost guns,” and may still acquire rifling marks that make—or complicate—identification in forensic labs. Recent forensic studies have confirmed that 3D-printed bullets can be functional and pick up class and individual characteristics, but these markings are sometimes harder to visualize due to layer artifacts [17], [18].

There is also growing interest in finding environmentally safer ammunition, especially lead-free designs, which has led researchers to explore polymer and composite alternatives. Moreover, the unpredictability and risks of so-called “less-lethal” projectiles (e.g., rubber bullets) highlight the need for carefully engineered, predictable solutions that could be manufactured under controlled conditions. In this area, 3D printing offers precise control over geometry and energy transfer [19], [20].

Despite this growing interest, there is still a lack of hard experimental data on the firing reliability, weapon performance, and penetration depth of fully 3D-printed polymer projectiles such as PLA. Without such data, it is difficult to build analytical models, define safety margins, or establish guidelines for controlled testing. This work aims to fill that gap by experimentally evaluating the firing reliability and penetration behavior of FDM-printed PLA projectiles for 9×19 mm ammunition, and by proposing a simple analytical model as a foundation for future studies.

1.1. Literature review

Research on AM and firearms mostly focuses on 3D printed parts, entire weapons or protective structures, while 3D printed ammunition, especially polymeric bullets and projectiles for small calibers, has very limited scientific data.

Regarding the polymer casings, company “TrueVelocity” (Garland, Texas, USA) offers 5.56 x 45 mm bullets with polymer-based casings. The manufacturer states that this production approach leads to increased projectile accuracy, less barrel wear and minimal muzzle deflection in fast projectiles. [21], [22], [23], [24]. A report from 2015 on light weapons and 3D printing stated that there was no proof of functional 3D printed ammunition at that time, with studies focusing only on parts and accessories [25]. Forensic tests on 3D printed firearms, like the single-shot Liberator pistol, showed that they can fire but usually fail after one or two shots. Bullets fired from these weapons can pick up rifling marks, but the marks are often hard to see because of the layer lines from printing [26], [27]. A more recent study from 2025 tested 3D printed PLA bullets on plywood, drywall, glass, and even soft body armor. The bullets penetrated the targets and left marks that could be traced back to the printer’s build plate [28]. Research on metal 3D printing also shows that stainless steel (316L) projectiles made by selective laser melting (SLM) have high precision and strength, but this is a completely different process compared to polymer FDM printing [29]. There is also a previously mentioned trend towards lead-free ammunition for environmental and health reasons, and tests on copper bullets and other alternatives show they often have lower muzzle energy and different penetration because of lower density compared to lead [30]. Unconventional designs like the Ruger/PolyCase ARX polymer-copper bullets, made with injection molding, show that alternative materials can be shaped for specific terminal effects [31]. In terms of customization, design and 3D print of non-standard bullet shapes can increase ammunition efficiency, as described in [32], where authors produced a fully lethal projectile of 12.7 mm calibre, but non-standard shape. Custom shaped bullets are also used in [33] for producing bio-degradable projectiles containing animal medicine. Authors in [34] 3D printed arrow tips from the ancient period and tested their penetration capabilities.

There is no peer-reviewed study that has tested fully 3D-printed PLA projectiles loaded into live 9×19 mm cartridges. Existing data on 3D-printed bullets is still very limited, with almost no hard measurements of firing reliability, weapon performance, or penetration depth. Most examples of 3D-printed small-caliber ammunition found online come from amateur experiments, blog posts, or social media videos, which often lack proper testing methodology, reproducibility, or detailed data. These sources are therefore unreliable and cannot be considered a solid technical reference.

1.2. Aim of the study

There is still very little reliable data on the firing reliability, overall weapon performance, and penetration depth of fully 3D-printed polymer projectiles such as PLA. Most information available today comes from amateur tests, often shared as short videos or posts on social media, without any clear methodology or reproducible measurements. Such sources cannot provide the technical detail needed to understand the real potential or risks of these projectiles, which is why controlled experimental research is necessary.

This study examines whether a 3D-printed PLA projectile can meet the basic requirements of internal, transitional, external, and terminal ballistics when used in standard 9×19 mm cartridges. The central assumption is that a carefully designed PLA bullet should be able to fire safely from a conventional handgun, exit the barrel without damaging the weapon, and deliver measurable penetration to a target medium.

To test this, PLA projectiles were produced using FDM 3D printing and evaluated for firing reliability, weapon integrity, and penetration depth against wooden targets. Besides penetration, the experiments also observed how the bullets deform after impact, how the firearm cycles during shooting, and whether the printed projectiles maintain structural stability throughout the process.

The broader aim of this research is to explore the feasibility of manufacturing specialized small-caliber ammunition using desktop 3D printing. The collected data can serve as a foundation for future analytical models, the development of predictable non-lethal ammunition, or even on-site production in conditions where traditional manufacturing is not practical.

2. Materials and methods

2.1. Design

This study represents the first step in a broader research effort on 3D-printed ammunition and its potential applications. It is therefore intentionally based on simple principles that require only a minimal level of engineering knowledge. One of the goals of this research is also to examine the risks of misuse, considering that FDM 3D printers are widely accessible and allow the production of bullets with very little technical expertise.

In line with this, no custom 3D model was designed for the purpose of this work. Instead, a ready-made model was downloaded for free and fully legally from one of the major online repositories of files intended for 3D printing [35]. The chosen model is a projectile for 9×19 mm ammunition, commonly known as „Parabellum“. Its dimensions are shown in Figure 1.

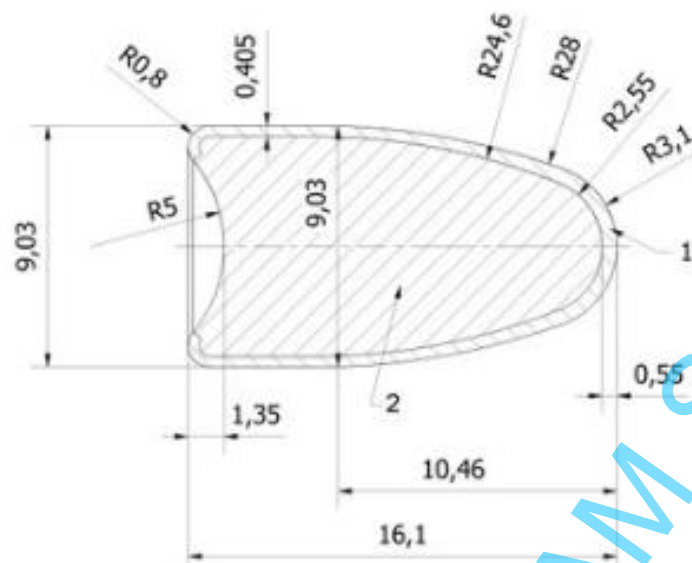


Fig. 1. Dimensions of a standard 9 x 19 mm projectile [36]

The 9×19 mm cartridge is NATO-standardized (STANAG 4090 / AEP-97), which guarantees interchangeability and well-defined performance limits across allied weapons. It is also the most commonly studied handgun caliber in modern forensic validation papers, which makes comparison with prior work straightforward and the results broadly relevant [37], [38].

2.2. 3D Printing

The polymer projectiles were manufactured using a desktop FDM 3D printer. FDM is currently the most accessible and widely used 3D printing technology due to its low cost, simplicity, and broad availability to both hobbyists and engineers [39], [40]. Due to the simplicity of the projectile model, the choice of FDM 3D printer is largely irrelevant—whether it's a miniature, homemade, or high-end industrial machine, the only differences may be in dimensional tolerances, which can easily be adjusted for in this case. This further highlights how feasible and accessible potential misuse of 3D printing for producing such ammunition really is [41]. PLA (polylactic acid) was selected as the printing material. PLA is a biodegradable thermoplastic commonly used in desktop 3D printing because it is easy to process, has low warping, and does not require a heated enclosure [42]. It is also cheaper than other polymers, easy to find, simple to use, and doesn't need any special storage, which makes it a good choice for this study based on the goals explained earlier. In order to ensure consistency, black PLA was selected for all samples, based on findings that filament color can impact the physical behavior of PLA prints [43]. The models were printed using a 0.4 mm nozzle and main parameters based on filament manufacturer guidelines presented in Table 1.

Parameter	Value
Layer height	0.2 mm
Infill density	100 %
Nozzle temperature	205 °C
Build plate temperature	60 °C
Print speed	200/300 mm/s

Table 1. Main printing parameters

A 100% infill density was used to ensure maximum strength. Projectiles were printed in a vertical orientation, with their axis aligned to the Z-axis of the printer. This alignment was chosen to minimize interlayer weaknesses in the direction of expected firing loads [44]. No raft or support structures were used, as the geometry did not require them. Model printing time was 5 minutes per projectile (without preparation), with total mass approximately 1 g.

All printed projectiles were visually inspected for defects such as delamination, voids, or warping. To simulate conditions of homemade ammunition production without specialized tools, a kinetic bullet puller was used to disassemble a factory

(Figure 2a) -made 9×19 mm cartridge. The original projectile was removed, while the primer, casing, and powder charge were preserved. The 3D-printed PLA projectile was then manually pressed into the original case, (Figure 2b).



Fig. 2. a) Disassembled bullet, b) Bullet with a 3D printed projectile and Factory made bullet

2.3. Experimental testing

For the first phase of the experiment, the powder charge was varied from 0.065 g to 0.13 g to ensure safety during testing, both for the shooter and the structural integrity of the weapon. Once functionality and accuracy were confirmed, the second phase used a powder charge of 0.26 g, which is slightly lower than the standard charge used for metal projectiles. The appearance of the test-ready cartridges is shown in Figure 3.



Fig. 3. 9 x 19 mm ammunition with polymer projectiles

At this stage of testing, due to the lack of existing data on the functionality of this type of ammunition, it was decided to conduct the experiment in two previously mentioned phases, on an open-range testing ground using a real firearm. The decision to use a real weapon instead of a reference barrel was based solely on cost considerations, since damaging a reference barrel would be significantly more expensive than damaging a standard pistol barrel. The firearm used for testing was a Grand Power K100 pistol with a barrel length of 108 mm.

As mentioned earlier, the first phase of testing involved firing projectiles with reduced powder charges, with the main goal of analyzing the internal ballistic cycle. The target was a fir board with a thickness of 25.4 mm (1"), which is commonly used in studies such as [32], [45] as a standard for evaluating projectile lethality. This is one of the historically

used methods to replace the often expensive and less accessible ballistic gel. The first phase did not include projectile velocity measurements, only visual inspection of the weapon's barrel and the test board.

A total of 6 projectiles were fired from various distances, and it was confirmed that this projectile type is safe to use and successfully completes all phases of the ballistic cycle.

After that, using a powder charge of 0.26 grams and a constant distance of 3 meters between the muzzle and the target, 10 projectiles were fired (5 test samples and 5 reference) at different points on the target to evaluate penetration capability. The average muzzle velocity was 250 m/s, with a standard deviation of 20 m/s. Projectile speed was measured using a ProChrono DLX chronograph. The appearance of the targets after testing is shown in Figure 4.

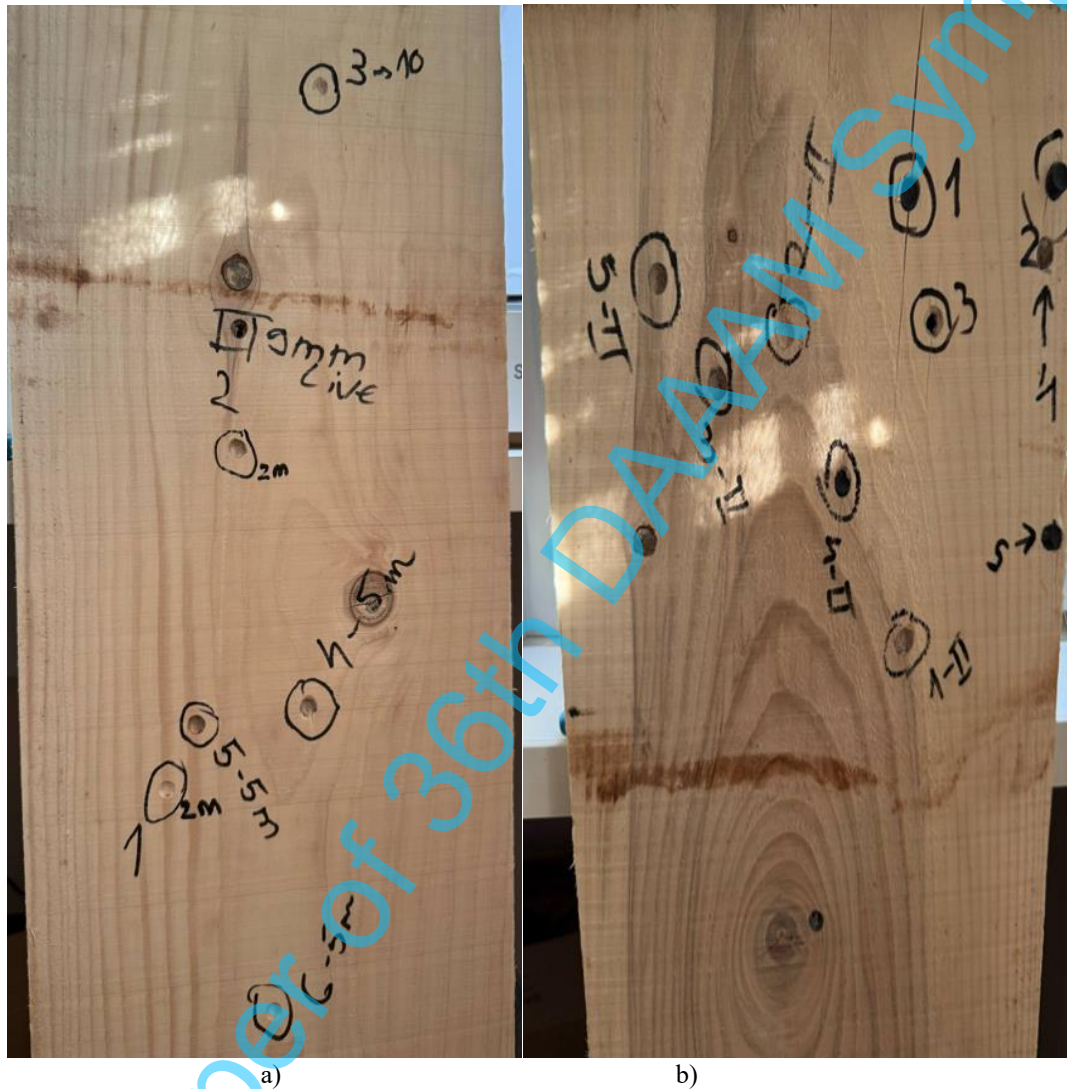


Fig. 4. Target appearance after testing, a) precision and reliability testing, b) penetration testing

An interesting fact is that none of the 16 projectiles deformed during the initial movement through the barrel, despite high pressure and temperature, nor upon high-velocity impact with the target, even though PLA is often considered as a material originally intended for low-load applications [46]. The appearance of the projectiles after firing and impact is shown in Figure 5. Marks from the barrel rifling are also visible.

Additional observations include that projectiles with reduced powder charges did not result in cartridge ejection, likely due to insufficient energy. In the first phase, the projectiles showed a deviation of less than 1 cm between the laser sight point and the actual point of impact.

Angular deviation (projectile yaw during flight) was recorded in only two cases and may be attributed to human error.



Fig. 5. Samples of projectiles after the experiment

3. Results and discussion

Analysis of the impact holes on both wooden targets revealed significant structural damage. Even on the target used in the first phase, penetration depths reached up to 1 cm in certain areas. Regarding the second phase, Table 2 presents the observed muzzle velocities and corresponding penetration depths.

Shot #	Velocity (m/s)	Penetration (mm)	Kinetic Energy (J)
1	231.3	16.0	26.74
2	237.1	12.8	28.11
3	278.9	25.4 (full)	38.91
4	287.1	20.0	41.23
5	238.7	15.8	28.49

Table 2. Observed values after the experiment

With an average penetration depth of 18 mm, the results suggest that 3D printed PLA projectiles weighing 1 g are not lethal under typical conditions (despite one recorded case of full penetration, which is insufficient according to the V50 standard), but they are capable of causing serious injuries. However, the 12.6 mm variation in penetration depth between the best and worst-performing projectile highlights the unreliability of such ammunition. It also illustrates why wooden targets are generally avoided in ballistic testing due to their material inhomogeneity and the strong correlation between impact location and penetration depth.

Based on the collected data, the average velocity was 254.6 m/s, with a spread of 55.8 m/s and a standard deviation of 26.2 m/s. Compared to a standard 9×19 mm cartridge, these results would typically be classified as representing aged, poorly stored, or inconsistent ammunition. Given that the tests were conducted outdoors and the projectile had extremely low mass, it is realistic to assume that each shot encountered different air resistance, even at a distance of just 3 meters, resulting in data dispersion.

Another contributing factor to result dispersion is the inherent inconsistency in 3D printing. Although the projectiles may appear identical, minor variations in print quality, such as porosity, inconsistent mass, microcracks, and imperfect centering, can significantly impact kinetic energy and flight stability. These imperfections lead to unstable trajectories and varying impact angles, where even slight deviations can alter penetration depth. Furthermore, variations in launch velocity suggest that no two projectiles were identical, resulting in inconsistent pressure build-up and barrel friction.

It is also noteworthy that the projectile with the highest muzzle velocity did not achieve the greatest penetration. Taking into account the initial kinetic energy and aerodynamic drag, it is possible to approximate the resistance of the wooden target to frontal impact in this specific experiment. The calculated average resistance is around 28 MPa, with a variation of approximately 8 MPa, representing a 30% difference. This again confirms that wooden targets are suboptimal for evaluating penetration performance.

Nevertheless, projectile #3 demonstrated that such a round can indeed be effective and potentially fatal against human targets. The results suggest that further research and development of 3D printed small-caliber projectiles is justified. Future studies should aim to standardize projectile fabrication, use homogeneous target materials, and maintain controlled testing conditions. Additionally, increasing the projectile mass, either by using denser materials or incorporating a mass insert into the projectile's center of gravity could significantly enhance performance.

One of the most important findings of this study is that a polymer with relatively low thermal resistance and moderate mechanical properties can still survive the launch phase and travel through a firearm barrel, a process characterized by extreme heat, pressure, and mechanical stress [47]. This observation further supports the feasibility of fully functional polymer firearms without any metallic components, which is a central focus of research in this domain. There is little doubt that in the coming years, interest in such studies will grow as modern manufacturing methods are increasingly applied to the development of special-purpose ammunition and weaponry.

Although regression analysis could not be reliably performed on this data set due to the material inhomogeneity of the wooden targets, the experiment provided valuable input data that can support future analytical modeling and the development of predictive models for projectile behavior.

4. Conclusion

The conducted experiments confirm that polymer-based 3D printed projectiles are not only functional but can also be dangerous and, in some cases, potentially lethal. Despite the simplicity of the setup, the rounds demonstrated the ability to survive firing, maintain structural integrity in flight, and achieve significant penetration into soft targets. These findings reinforce the need for more rigorous ballistic testing using standardized materials such as calibrated ballistic gel instead of wood, in order to reduce variability and obtain more reliable penetration data.

Future studies must focus on improving the consistency of projectile manufacturing to reduce dispersion in muzzle velocity and kinetic energy. This includes refining print quality, exploring different infill structures, and testing variations in projectile tip geometry, such as spiral features, vents, or other shape optimizations that could affect flight stability and penetration behavior.

Moreover, traditional forensic methods for analyzing rifling marks should be applied to 3D printed bullets to evaluate their traceability and potential forensic implications. The current study has shown that even low-cost, entry-level FDM printing techniques are sufficient to produce functional ammunition without requiring any advanced knowledge or specialized equipment—a significant observation in itself.

The results serve as a successful proof-of-concept for a low-barrier, fully printable round and confirm that further development is both technically feasible and justified. In future iterations, the research will involve controlled environments, standardized targets, more advanced measuring systems, and greater sample sizes. There is also a realistic possibility of developing a completely polymer-based cartridge, possibly incorporating electronic initiation systems. Subsequent research will aim to establish controlled analytical and numerical models that can reliably predict projectile behavior, while also ensuring safety in use and exploring the full potential—and limits—of such additive-manufactured ammunition.

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