■ Research Article

Development of Composite Wax Filament for Fused Deposition Modeling in the Jewelry Industry

Thawatchai Pattha[1], Subongkoj Topaiboul[2]* and Peerawat Luesak[3]

[1]Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna
128 Huay Kaew Road, Muang, Chiang Mai, Thailand, 50300
[2]College of Integrated Science and Technology Rajamangala University of Science and Technology
98 Moo 8, Pa Pong Subdistrict, Doi Saket District, Chiang Mai 50220, Thailand
[3]Department of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna, Chiang Rai
99 Moo 10, Sai Khao Subdistrict, Phan District, Chiang Rai Province, 57120, Thailand

Abstract

The brittleness and extrusion instability of conventional wax materials present significant challenges in Fused Deposition Modeling (FDM)-based jewelry prototyping. To address these limitations, this study investigated the incorporation of High-Density Polyethylene (HDPE) into injection-grade wax to enhance mechanical strength, elongation, and thermal stability. Composite wax filaments were formulated at three weight ratios—40:60, 50:50, and 60:40 (wax: HDPE)—and tested for rheological and mechanical performance using Dynamic Mechanical Analysis (DMA) and Ultimate Tensile Strength (UTS) testing. The results showed that the 50:50 wax-HDPE composite achieved the best balance between tensile strength (19.11 ± 0.41 MPa) and elongation (17.84%), while also exhibiting superior thermal resistance compared to pure wax, with a 27% increase in phase transition temperature. Although the composite remained mechanically weaker than ABS and PETG, it demonstrated superior flexibility and stability relative to PLA, making it suitable for applications requiring moderate mechanical strength and high print resolution. The findings highlighted the practical applicability of the wax-HDPE 50:50 formulations in jewelry prototyping, particularly for intricate, dimensionally stable components where traditional wax fails. This composite provided a viable material solution bridging conventional investment casting and modern additive manufacturing techniques.

Keywords: Composite wax filament, Fused Deposition Modeling, Jewelry prototyping.

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***Corresponding Author:**
thawatchaipattha2537@gmail.com

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1. Introduction

Wax-based prototyping has long played a crucial role in the jewelry manufacturing industry, traditionally relying on skilled artisans for hand-carved patterns to facilitate production (Dolgov et al., 2023). However, a key limitation of wax lies in its brittleness, making it highly susceptible to deformation under unfavorable temperature conditions and unsuitable for intricate designs requiring high precision, such as prong settings or filigree structures (Zhilin et al., 2022). In contrast, metal prototypes offer superior strength and dimensional stability (Sásik et al., 2020). While wax provides advantages in flexibility, ease of carving, and reusability through remelting and reshaping, its fragility and sensitivity to temperature fluctuations remain significant challenges (Liu et al., 2023; Zhou et al., 2024). The type of wax used also influences the final properties of the prototype, with blue wax offering higher ductility. In contrast, green wax, being more brittle, is preferred for silver jewelry due to its ability to retain fine details (Karantonas, 2022). Advances in additive manufacturing, particularly Fused Deposition Modeling (FDM), have drawn attention as a cost-effective method for fabricating high-resolution prototypes (Goh et al., 2020). However, challenges persist in utilizing wax-based materials in FDM, particularly in achieving controlled flow behavior and maintaining structural integrity during deposition (Forstner et al., 2024). These limitations hinder the precision and consistency of printed components, necessitating further material development to enhance the suitability of wax-based filaments for jewelry applications (Szabó et al., 2022).

Although previous research has focused on enhancing the properties of wax for use in Fused Deposition Modeling (FDM), there remains a lack of studies on the incorporation of High-Density Polyethylene (HDPE) to improve its viscosity and solidification behavior during layer-by-layer deposition. The development of a wax-HDPE composite represents a promising approach to addressing these limitations by optimizing the material's rheological properties for FDM applications. Prior studies have identified key challenges related to the flow consistency and thermal stability of wax during printing, resulting in variations in dimensional accuracy and surface quality, which hinder its broader adoption in the jewelry industry. Research by Rahmalina et al. (2023) on paraffin-HDPE blends for Form-Stable Phase Change Materials (FSPCMs) demonstrated that an optimal HDPE ratio enhances durability and minimizes leakage, but this concept has yet to be applied to wax formulations for FDM-based prototyping. Similarly, Topaiboul et al. (2021) investigated the feasibility of printing wax using a modified Fused Deposition Modeling (FDM) system for jewelry applications, reporting that while wax could be extruded, its inconsistent flow properties led to low-resolution outputs, necessitating further refinement. Moreover, Ahmad and Yahya (2023) analyzed the effects of 3D printing parameters on the mechanical performance of Acrylonitrile Butadiene Styrene (ABS), emphasizing the influence of factors such as melting temperature, print speed, layer thickness, and infill pattern. The study highlighted that adjusting extrusion temperature and optimizing print speed significantly improved tensile strength, while reducing layer thickness and employing strategic infill designs enhanced structural integrity. These findings underscore the need for further investigation into composite wax formulations, particularly in refining their flow behavior and thermal characteristics to achieve high-precision fabrication in additive manufacturing.

The key research gap lies in developing a wax-HDPE composite material to improve viscosity, flow behavior, and stability during FDM. This study aims to engineer a composite wax filament incorporating HDPE to optimize mechanical properties and rheological characteristics for FDM-based jewelry prototyping. The research investigated the compatibility and optimal formulation of injection-grade wax blended with HDPE, focusing on the effects of varying compositions on material behavior. Dynamic Mechanical Analysis (DMA) and Universal Testing Machine (UTM) testing for Ultimate Tensile Strength (UTS) assessed viscosity, tensile strength, and phase transition properties. The feasibility of fabricating composite wax structures via FDM was also ~~be~~ evaluated. Expected outcomes include improved printing performance, reduced material limitations, and enhanced cost efficiency for jewelry prototype manufacturing, ultimately expanding the applicability of 3D printing technology in the jewelry industry.

2. Research Objectives

2.1 To develop a wax-HDPE composite filament for FDM with enhanced mechanical strength, elongation, and thermal stability for jewelry prototyping.

2.2 To assess the composite's rheological and mechanical properties via DMA and UTM, identifying the optimal formulation for improved printability.

3. Literature Review

The rise of additive manufacturing has broadened wax applications in jewelry prototyping, yet conventional wax lacks mechanical strength, thermal stability, and flow control, limiting its use in Fused Deposition Modeling (FDM). To overcome these issues, researchers have modified wax compositions, notably by adding High-Density Polyethylene (HDPE). The following sections review wax-based materials in additive manufacturing and composite wax-HDPE filaments, emphasizing their role in improving processability, print resolution, and structural integrity.

3.1 Wax- Based Materials and Their Applications in Additive Manufacturing

3.1.1 Wax Formulation for Investment Casting

Wax-based materials have gained significant attention in additive manufacturing (AM), particularly in investment casting, due to their ability to enhance prototype precision, dimensional accuracy, and process efficiency. Tewo et al. (2019) conducted a comprehensive review on the formulations, development, and characterization techniques of investment casting patterns, exploring various wax types, their limitations, and the effects of fillers and additives on unfilled waxes. Cheng et al. (2024) integrated 3D wax printing with investment casting, showcasing its applicability in metal optical lens fabrication, where surface quality and geometric precision are critical. Prianto et al. (2023) further examined wax-based AM in craft goods and jewelry prototyping, highlighting its ability to reproduce intricate designs with high resolution.

3.1.2 Wax Behavior in Material Extrusion (FDM)

While traditionally used in casting, wax materials are now being applied to material extrusion processes, especially Fused Deposition Modeling (FDM). Forstner et al. (2024) investigated the effect of wax incorporation on feedstock processing for material extrusion, emphasizing its role in improving rheological behavior and extrusion stability in metal-based AM applications.

3.1.3 Polymer-Based Composites for FDM

Fused Deposition Modeling (FDM) has emerged as a key technique for processing polymer-based composites, particularly in applications requiring enhanced mechanical performance and flow control. Ahmadifar et al. (2021) conducted a comprehensive review of polymer composites in FDM, revealing that filler dispersion, material composition, and processing parameters significantly impact structural integrity and print quality. However, challenges such as inconsistent flow behavior, interlayer adhesion deficiencies, and anisotropic mechanical properties remain obstacles to achieving uniformity in printed structures.

3.1.4 Rheological Control and Filler Interactions

Complementing these studies, Rueda et al. (2017) examined the rheological behavior of polymer-filler systems, detailing the influence of particle morphology, filler concentration, and shear rate on viscosity and extrusion performance.

The study underscored the necessity of precise rheological control and optimized filler-matrix interactions to achieve uniform material flow, dimensional consistency, and mechanical stability in FDM-based composites.

3.2 Composite Materials for 3D Printing: HDPE and Wax Blends

3.2.1 HDPE-Based Composites in Material Extrusion

Advancements in composite materials for additive manufacturing (AM) have expanded the applicability of high-density polyethylene (HDPE) in material extrusion and investment casting. Dalloul et al. (2022) developed a nanocellulose-reinforced HDPE composite filament, demonstrating enhanced mechanical properties, processability, and geometric fidelity in extrusion-based 3D printing. Similarly, Vidakis et al. (2023) investigated HDPE/carbon black composites, emphasizing improvements in thermal conductivity, rheological behavior, and mechanical performance—critical factors for reliable extrusion in AM systems.

3.2.2 Wax-Based Composites for Precision Casting

While HDPE is often noted for mechanical reinforcement, wax-based blends remain essential in investment casting due to their surface quality and fine-detail replication. Mukhtarkhanov et al. (2022) optimized process parameters for 3D-printed investment casting wax patterns, resulting in improved dimensional stability and post-processing efficiency. Szabó et al. (2022) examined the rheological and mechanical characteristics of flexible wax materials, reinforcing their value in high-precision manufacturing contexts.

3.2.3 Functional Applications of HDPE Composites

The functional versatility of HDPE extends beyond structural applications. Freeman et al. (2018) explored PCM/HDPE composites for battery thermal management, highlighting the importance of thermal conductivity and phase-change stability. This functional integration opens avenues for HDPE blends in energy-sensitive or temperature-regulated AM applications.

3.2.4 Hybrid Material Designs and Process Optimization

The push for high-performance AM materials has led to innovations in polymer hybridization. Schirmeister et al. (2021) introduced digitally tuned all-polyethylene composites, using nanostructure control to enhance print stability and mechanical integrity. Bisin et al. (2021) investigated paraffin-polymer fuel composites for 3D printing, revealing how material modifications can influence flow behavior and strength retention.

Collectively, these studies underscore the importance of rheological optimization, strategic material formulation, and process refinement in improving the printability, dimensional accuracy, and functional properties of HDPE and wax- based composites in additive manufacturing systems.

4. Materials and Methods

The study used green wax and HDPE to develop composite materials optimized for 3D printing in jewelry applications. These materials were compared with ABS, PETG, and PLA to evaluate their printability, mechanical properties, and detail resolution. The selection of each material was based on its performance in FDM-based prototyping and its potential to enhance manufacturing precision in the jewelry industry, with details as follows:

4.1 Materials

The primary material used in this study was injection-grade green wax (Spring Wax, Model SW 301 AA, Grade A), chosen for its superior ability to capture intricate details, making it ideal for jewelry prototyping. Widely used in the jewelry industry, green wax is brittle yet easy to sand and file, with high detail retention that is especially beneficial for creating complex designs in silver jewelry. Additionally, High-Density Polyethylene (HDPE) from TCR-Plastic (Grade A, injection-molding type) was used as a composite material. Known for its high toughness, chemical resistance, and structural integrity, HDPE has a density of 0.941-0.965 g/cm³ and a melting point of 135°C, offering excellent phase transition stability. These properties enhance the viscosity and flow behavior of wax, optimizing it for Fused Deposition Modeling (FDM) 3D printing.

The commercial grade filament from X3D technology, including ABS, PETG, and PLA, was chosen in order to benchmark with all ratio wax-HDPE composites in terms of strength properties. These results can be used to determine the possibility of introducing the new composites on the current FDM 3D printer.

4.2 Methods

4.2.1 Material Preparation

The materials used in the study, wax and HDPE were mixed in ratios of 40:60, 50:50, and 60:40 to determine the most suitable composition for filament production. The materials were uniformly blended using a twin-screw extruder at a temperature range of 140-180°C and an injection pressure of approximately 8-10 MPa to ensure consistent material flow.

The twin-screw extruder featured a co-rotating, intermeshing screw configuration with a length-to-diameter (L/D) ratio of 40:1. The material residence time during extrusion was approximately 2.5–3 minutes, depending on the wax-to-HDPE ratio. After exiting the die, the filament was passed through a controlled air-cooling channel, which maintained an average cooling rate of approximately 5–8°C per second to ensure dimensional stability and prevent bubble formation.

The filament was extruded at a nozzle temperature of 110-140°C to achieve uniform thickness without air bubbles. A square mold with dimensions of 200 mm × 200 mm and a thickness of 4 mm was used to prepare the sheet for subsequent testing.

4.2.2 Specimen Preparation

The rectangular sheets with dimensions of 200 mm × 200 mm and a thickness of 4 mm (Figure 1) were prepared for two types of tests:

Dynamic Mechanical Analysis (DMA): The specimens were molded into cylindrical shapes (Figure 2 (a)) with a height of 1.75±0.1 mm (Figure 2 (b)) and a diameter of 6.65±0.1 mm (Figure 2 (c)). A total of 50 specimens were prepared, consisting of 10 wax specimens, 10 HDPE specimens, and 10 specimens for each ratio of Wax-HDPE composites.

Figure 1: Sheet prepared for testing

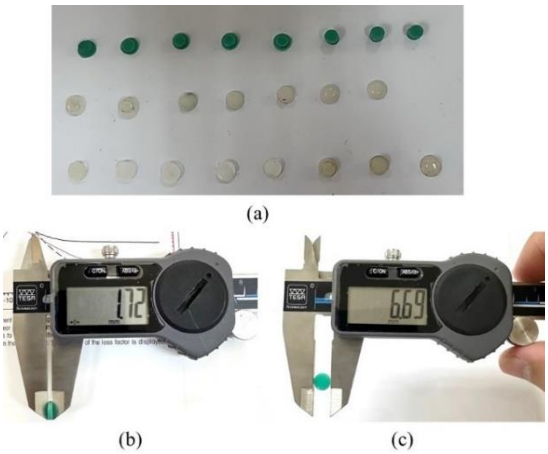

Figure 2: Specimens for DMA

Ultimate Tensile Strength (UTS): A total of 80 specimens were prepared: 10 for wax, 10 for HDPE, 10 for each ratio of Wax-HDPE composites, and 10 each for commercial ABS, PETG, and PLA for comparison. The specimens were prepared according to ASTM D638 Type IV, a common standard for plastics and composites (as shown in Figure 3).

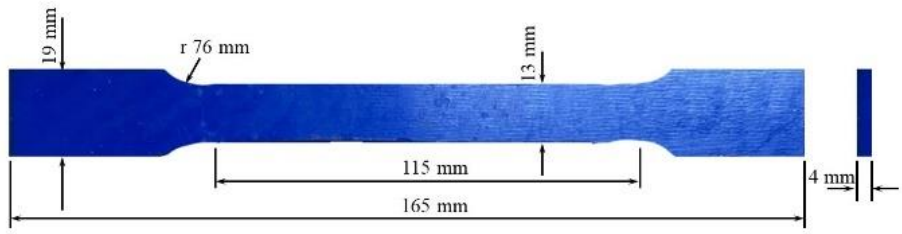

Figure 3: Specimens for UTS

4.2.3 Material Testing

Since pure wax has been previously reported as challenging for 3D printing due to uncontrollable flow behavior during extrusion, DMA was conducted to analyze its solid-liquid phase transition. As shown in Figure 4, Dynamic Mechanical Analysis (DMA) was performed within a temperature range of 0°C to 85°C for wax and 0°C to 185°C for HDPE, with a heating rate of 2°C/min under a tensile load frequency of 1 Hz. Wax-HDPE composites at ratios of 40:60, 50:50, and 60:40 were tested within a temperature range of 0°C to 110°C.

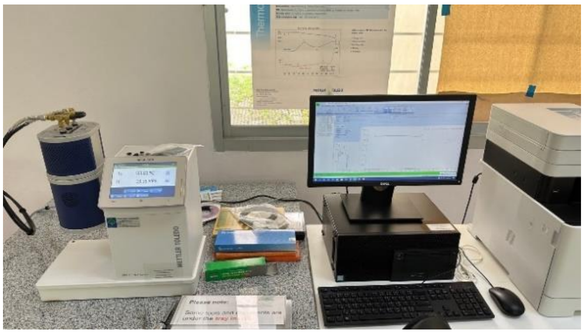

Figure 4: DMA testing machine

Ultimate Tensile Strength (UTS) testing, as shown in Figure 5, was conducted using a Universal Testing Machine (UTM) equipped with a 10-kN load cell at a constant extension rate of 10 mm/min and a test temperature of 25°C. Ten specimens of each material were carefully prepared as previously described. These size specifications and test conditions are critical for accurately assessing the mechanical properties of the materials and ensuring reliable comparisons when evaluating tensile strength and elongation properties.

Figure 5: Universal testing machine

4.2.4 Filament Fabrication and Trial Printing

After determining the optimal material composition from the test results, the selected formulation was extruded into filament form. The production of wax-HDPE composite filaments with a diameter of 1.75 mm is carried out using a twin-screw extrusion process. The material was melted at a temperature range of 140–180°C and extruded through a nozzle maintained at 110–140°C to regulate flow consistency. The extruded filament was then drawn from the nozzle and gradually cooled to prevent air entrapment and deformation. Finally, the filament was wound into spools with a uniform diameter of 1.75 mm, as shown in Figure 6, before being used in Fused Deposition Modeling (FDM) 3D printing systems.

The wax-HDPE composite filament, extruded to a diameter of 1.75 mm, was then processed using an FDM 3D printer, as shown in Figure 8. The filament was utilized in the printing process, with specimens fabricated at a layer height of 300 microns (0.3 mm) and a printing speed of 40–60 mm/s to form cubic structures measuring 2 × 2 × 2 cm, as required, as shown in Figure 9.

Figure 6: Extruded filament

5. Results

5.1 Results of Dynamic Mechanical Analysis

The thermal and mechanical properties of injection-grade wax, HDPE, and wax-HDPE composites (at ratios of 40:60, 50:50, and 60:40) were analyzed using Dynamic Mechanical Analysis (DMA), focusing on phase transition temperatures, modulus variations with temperature, and structural stability at elevated temperatures.

Wax: The phase transition temperature of injection-grade wax ranged from 76°C to 81°C, during which its storage modulus (E') decreased significantly, indicating a transition from a solid to a liquid state. At 25°C, the wax exhibited a modulus of 1.5 GPa, which reduced to 0.4 GPa at 80°C, resulting in a 73% reduction. This sharp decline marked full material softening and liquefaction beyond 80°C, limiting its mechanical integrity at higher temperatures. The loss modulus (E') increased between 79°C and 81°C, signifying high energy dissipation and structural instability.

High-Density Polyethylene: HDPE exhibited a phase transition temperature range of 136°C to 152°C, with a modulus reduction from 2.8 GPa at 25°C to 0.8 GPa at 150°C (a 71% reduction). A slight modulus increase between 140°C and 142°C indicated semi-crystalline behavior or partial recrystallization, temporarily enhancing strength. HDPE maintained better structural integrity than wax, but beyond 152°C, the material underwent significant softening and permanent deformation.

Wax-HDPE Composites (40:60, 50:50, and 60:40): The composite materials demonstrated improved phase transition temperatures and mechanical stability compared to pure wax. The phase transition temperature for all composites ranged between 98°C and 105°C, with a modulus at 25°C of 2.2 GPa for the 40:60 ratios, 2.3 GPa for the 50:50 ratios, and 2.0 GPa for the 60:40 ratios. These values were significantly higher than wax alone. The 50:50 composite retained 1.1 GPa at 100°C, exhibiting superior modulus retention compared to wax, which fully softened at 80°C. The percentage reduction in modulus for the composites was 55%, 52%, and 56% for the 40:60, 50:50, and 60:40 ratios respectively, highlighting enhanced structural stability across all ratios.

Comparison and Suitability for Fused Deposition Modeling (FDM): Table 1 summarized the DMA results for all materials. Pure wax demonstrated a low phase transition temperature and significant modulus reduction, highlighting its rapid degradation at elevated temperatures. In contrast, HDPE exhibited a higher phase transition temperature but experienced substantial softening beyond 150°C. The wax-HDPE composited, particularly the 50:50 ratios, exhibited the best balance of phase transition temperature (98–105°C) and modulus retention (52% reduction), making it the most suitable material for FDM applications.

Table 1 Comparison of dynamic mechanical analysis for each material.

Tested Material	Phase Transition Temperature (Ta, °C)	Maximum Strength (E' at 25°C)	Minimum Strength (E' at Tmax)	Percentage Change (%)
Wax	76 - 81	1.5 GPa	0.4 GPa	-73%
HDPE	136 - 152	2.8 GPa	0.8 GPa	-71%
Wax-HDPE Composite (40:60)	98 - 105	2.2 GPa	1.0 GPa	-55%
Wax-HDPE Composite (50:50)	100 - 108	2.3 GPa	1.1 GPa	-52%
Wax-HDPE Composite (60:40)	95 - 103	2.0 GPa	0.9 GPa	-56%

The improved thermal and mechanical properties of wax-HDPE composites result from the synergistic interaction between the flexibility of wax and the semi-crystalline structure of HDPE, which enhances stability under thermal loading. The elevated phase transition temperature (Ta) and reduced modulus loss indicate superior resistance to thermal softening, making these composites well-suited for Fused Deposition Modeling (FDM) prototyping. Among the tested ratios, the 50:50 composite exhibited the most balanced thermal and mechanical characteristics, highlighting its potential for applications that demand both printability and high thermal resistance, particularly in jewelry manufacturing.

5.2 Results of Ultimate Tensile Strength Testing

The tensile strength testing of Wax-HDPE composites (40:60, 50:50, 60:40) was compared against three commonly used thermoplastics in 3D printing: ABS, PETG, and PLA. The key mechanical properties analyzed include UTS, strain at break, and failure behavior.

Table 2 Comparative tensile properties (mean ± SD) of Wax-HDPE composites and common 3D Printing Thermoplastics.

Material	Max Stress (UTS)	Strain at Break	Failure Behavior
Wax-HDPE (40:60)	20.45 ± 0.38 MPa	12.37%	High strength, moderate ductility
Wax-HDPE (50:50)	19.11 ± 0.41 MPa	17.84%	Balanced strength & flexibility
Wax-HDPE (60:40)	19.07 ± 0.33 MPa	15.64%	Moderate strength, high elongation
ABS	29.13 ± 0.47 MPa	25.06%	High strength, brittle failure
PETG	34.24 ± 0.39 MPa	40.51%	High strength, ductile
PLA	4.45 ± 0.22 MPa	3.18%	Low strength, brittle failure

Figure 7 illustrates the comparative tensile performance of Wax-HDPE composites and standard thermoplastics used in FDM. The chart reveals that Wax-HDPE (50:50) achieved a balanced combination of tensile strength and elongation, while PETG demonstrated superior ductility.

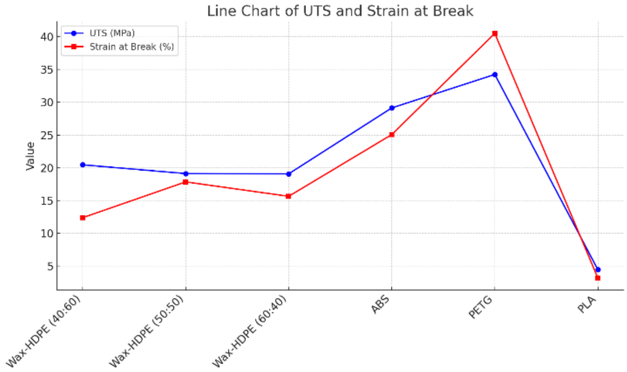

Figure 7: UTS and strain comparison of Wax-HDPE and standard 3D printing materials.

Table 2 gives the performance analysis comparing the tensile strength of Wax-HDPE composites with ABS, PETG, and PLA. Strength Comparison: Wax-HDPE composites exhibit lower tensile strength compared to ABS and PETG, with maximum stress values ranging from 19.07±0.33 MPa to 20.45±0.38 MPa, whereas ABS and PETG reach up to 35 MPa and 40 MPa respectively. This suggests that Wax-HDPE composites are not as strong as engineering-grade polymers like ABS and PETG, which are designed for high-stress applications. PLA, on the other hand, has a significantly lower tensile strength (2.5–6 MPa) than Wax-HDPE composites, indicating that Wax-HDPE materials outperform PLA in terms of load-bearing capacity.

Ductility and Elongation: Wax-HDPE composites exhibit significantly higher strain at break than ABS and PLA. The highest elongation among Wax-HDPE samples (17.84% for 50:50) was much greater than that of ABS (0.25–0.30%) and PLA (0.02–0.05%), meaning Wax-HDPE materials are more flexible and less prone to sudden brittle failure. PETG, however, outperforms Wax-HDPE in terms of ductility, with elongation values reaching 0.55 strain (55%), suggesting that PETG is better suited for applications requiring high flexibility and impact resistance.

Failure Behavior: ABS exhibits brittle failure, meaning it tends to crack or snap under excessive load rather than deform plastically. PETG displays a more ductile failure mode, similar to Wax-HDPE (50:50 and 60:40), allowing for better shock absorption. PLA is highly brittle and fractures suddenly under stress, making it the weakest material in this comparison. Wax-HDPE (50:50 and 60:40) exhibits a balance between strength and ductility, preventing sudden failure, making them more adaptable than ABS and PLA in certain applications.

Therefore, Wax-HDPE composites outperform PLA in terms of tensile strength and flexibility, making them a superior alternative for applications requiring moderate mechanical durability. In comparison to PETG, Wax-HDPE (50:50 and 60:40) exhibits similar ductility, making them viable for flexible component applications where mechanical adaptability is required. However, in terms of tensile strength, Wax-HDPE remains weaker than both ABS and PETG, which are better suited for load-bearing applications where high mechanical stress is a critical factor.

The best application cases for Wax-HDPE composites are determined by their balance between flexibility and moderate strength. Based on the performance comparison, Wax-HDPE composites are most suitable for applications such as mold-based fabrication and prototyping, where dimensional stability and impact resistance are essential. They are also ideal for 3D-printed components that require moderate mechanical strength without excessive brittleness, including casings, lightweight enclosures, and decorative parts. Additionally, Wax-HDPE composites are well-suited for low-stress applications, where PLA would be too brittle, but ABS or PETG would be unnecessarily strong or cost-prohibitive.

In conclusion, while Wax-HDPE composites do not surpass ABS or PETG in tensile strength, they provide an excellent balance of mechanical properties that make them a viable alternative in flexible and impact-resistant applications, especially where cost and material adaptability are considerations.

5.3 Result of Trial Printing of 3D Shapes

The 3D printing trials using Wax-HDPE composites demonstrated that the 50:50 ratio provided the best balance between strength (19.11 MPa) and elongation (17.84%), making it the most suitable formulation for FDM 3D printing. The filament was processed using an FDM 3D printer (Figure 8), and the printed specimens, designed as 2 × 2 × 2 cm cubes (Figure 9), showed minor shrinkage but maintained dimensional accuracy. The surface texture was relatively smooth, and the layer-by-layer deposition was consistent, with minimal deformation. However, warping at the base of the printed objects was observed due to the rapid cooling of the composite material, leading to contraction and slight distortion.

This warping behavior was especially pronounced in the 40:60 and 60:40 compositions due to higher wax content, which increases shrinkage upon cooling. To mitigate this issue, several approaches are recommended, including the use of a heated bed maintained at 50–60°C, application of adhesion aids such as glue sticks or polyimide tape, and enclosing the printer to minimize ambient temperature fluctuations. Slowing down the initial layer print speed and increasing nozzle temperature can also improve first-layer adhesion. These measures help relieve internal stress and prevent edge lifting during the cooling phase.

To address this issue, further optimization is needed, including adjustments to cooling rates, modifications to printing parameters (such as nozzle temperature, print speed, and heated bed utilization), and potential formulation enhancements through the incorporation of additives to improve flexibility and thermal stability. Despite these challenges, the Wax-HDPE (50:50) composite exhibits strong potential for FDM-based 3D printing, offering a well-balanced combination of printability, mechanical integrity, and thermal performance.

Figure 8 FDM 3D printer.

Figure 9 Wax-HDPE composite cube specimen.

6. Discussion

The findings of this study aligned with previous research on the enhancement of wax-based filaments for additive manufacturing, particularly in FDM applications. Conventional wax filaments, while advantageous for investment casting and jewelry prototyping, exhibit brittle failure, poor dimensional stability, and inconsistent extrusion behavior (Dolgov et al., 2023; Zhilin et al., 2022). The incorporation of HDPE into the wax matrix significantly improved these limitations by increasing tensile strength, strain at break, and thermal stability, as evidenced by the 20.45 MPa tensile strength of the 40:60 Wax-HDPE formulation, which outperformed traditional wax compositions used in FDM (Forstner et al., 2024; Szabó et al., 2022).

The results further confirmed that the flow behavior and extrusion stability of wax-based filaments improve with the addition of HDPE, supporting the findings of Rahmalina et al. (2023), who reported similar enhancements in phase stability for paraffin-HDPE blends. Compared to conventional ABS, PETG, and PLA materials, the Wax-HDPE composite exhibits moderate tensile strength but superior ductility, making it a more viable option for flexible, high-precision applications (Ahmad and Yahya, 2023). While PETG remains the strongest and most ductile material for 3D printing applications, Wax-HDPE (50:50) provides an optimal balance of flexibility and mechanical stability, addressing key challenges previously identified in wax-based FDM research (Mukhtarkhanov et al., 2022; Topaiboul et al., 2021).

Moreover, the thermal performance of the Wax-HDPE composite demonstrated a significant improvement over pure wax, particularly in phase transition temperatures, with an increase of 27% compared to injection-grade wax. These results reinforce the work of Cheng et al. (2024) and Prianto et al. (2023), who emphasized the necessity of material modifications to improve wax-based additive manufacturing processes. However, further refinement is required to optimize print resolution and layer adhesion, as observed in prior research on wax-polymer hybrid materials (Freeman et al., 2018; Vidakis et al., 2023).

7. Conclusion

This study confirmed that wax-HDPE composites represented a significant advance in 3D-printable wax materials, overcoming the brittleness and extrusion instability of conventional wax filaments. The balanced strength, elongation properties, and improved thermal behavior made these composites highly applicable for jewelry prototyping, particularly for intricate and high-resolution designs.

The development of Wax-HDPE composite filaments for FDM-based 3D printing in the jewelry industry represented a novel approach to enhancing the mechanical strength, printability, and structural integrity of wax-based materials. The results indicated that Wax-HDPE (40:60) exhibited the highest tensile strength (20.45 MPa), while Wax-HDPE (50:50) provided the best balance between strength and flexibility, making it the most versatile formulation for jewelry prototyping applications.

These improvements greatly enhanced investment casting workflows by providing the dimensional precision and high-resolution pattern fabrication essential for creating intricate jewelry designs—such as filigree structures, prong settings, and detailed engraving patterns. Unlike conventional wax filaments, which suffer from brittle failure and inconsistent deposition, the optimized Wax-HDPE composite offers improved thermal resistance and controlled layer-by-layer deposition, leading to more precise and repeatable manufacturing outcomes.

Future research should explore further optimization of wax-polymer blends, particularly with nano-fillers or reinforcement additives to enhance mechanical performance and print resolution. Additionally, refining FDM printing parameters, such as extrusion temperature, print speed, and support material integration, will further improve the functional capabilities of Wax-HDPE filaments for high-precision jewelry manufacturing. The integration of sustainable, bio-based polymers into wax formulations also presents an opportunity to develop eco-friendly alternatives for casting applications, supporting sustainable jewelry production methods.

In conclusion, the study successfully demonstrated that Wax-HDPE composite filaments provided a practical and scalable solution for high-resolution jewelry prototyping, bridging the gap between traditional investment casting techniques and modern additive manufacturing technologies.

8. Acknowledgment

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