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3D Printing for Kiswah Adornment: An Applied Investigation into Additive Manufacturing as an Alternative to Gold Thread Embroidery

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Abstract

The Kiswah, the embroidered black silk covering of the Holy Kaaba in Makkah, is the most prestigious work of Islamic textile craftsmanship and is renewed annually at substantial cost. The traditional gold and silver thread embroidery is vulnerable to ultraviolet, thermal, and hydric degradation, and the artisanal labour pool required to execute it is contracting. This applied study investigates the technical feasibility of substituting selected components of the gold thread ornamentation with three-dimensionally printed elements. Three candidate material systems were evaluated: gold-look polylactic acid (PLA) processed by fused deposition modelling, ultraviolet-stabilised photopolymer resin loaded with metallic pigment processed by stereolithography (SLA), and metal-loaded glycol-modified polyethylene terephthalate (PETG-Cu). Eight specimens per material - comprising 24 printed test pieces and four traditional embroidered control specimens - were subjected to a 12-month exposure protocol on an outdoor test rig in Makkah, with periodic instrumented assessment of colour change (delta E), gloss retention, adhesion to the silk substrate, and dimensional stability. Results demonstrate that all three printed material systems exhibited measurable degradation, but that UV-stabilised SLA resin and PETG-Cu both retained colour and adhesion sufficient to be considered candidate substitutes for non-contact ornamental elements. Gold-look PLA failed thermal stability criteria within the first three summer months. None of the printed systems matched the directional metallic sheen of traditional couched zari thread. The study concludes that AM is technically feasible for selected ornamental components but, in its current state, is best deployed in a hybrid workflow alongside traditional embroidery rather than as a full substitute.

Keywords: *additive manufacturing; Kiswah; gold thread; zari; thuluth calligraphy; outdoor weathering; PLA; PETG; SLA resin; cultural heritage; Vision 2030.*

Introduction

The Holy Kaaba in Makkah is enveloped each Hijri year by the Kiswah, a black silk covering bearing Qur'anic inscriptions in raised gold-thread thuluth calligraphy. The annual production at the Kiswah Factory in Makkah employs approximately 200 to 300 craftsmen for an eight to twelve-month cycle, consumes between 120 and 200 kilograms of metallic thread (gold gilt over silver-base bullion), and is reported to cost in excess of GBP 3.3 million. The economic, environmental, and labour pressures associated with this production model, combined with the strategic priorities of Saudi Vision 2030, have prompted scholarly interest in evaluating advanced manufacturing technologies as potential complements to traditional practice.

The conceptual basis for this investigation has been developed in a companion paper, which proposes the Sacred Additive Manufacturing (SAM) framework comprising four evaluative

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domains: sacred and cultural fidelity, material and environmental performance, production economics and sustainability, and hybrid craft–digital workflow. The present paper reports on the first applied empirical study conducted within that framework. The investigation focuses specifically on Domain 2 (material and environmental performance) and Domain 1 (cultural fidelity, addressed through optical and tactile measurement), with preliminary observations on Domain 3 (cost and labour). Domain 4 considerations require stakeholder engagement that lies beyond the scope of the present study.

Research Questions

This study addresses four research questions:

- Can three-dimensionally printed materials retain visual fidelity to traditional couched gold-thread embroidery - specifically with respect to colour, gloss, and surface relief - over a one-year service period under Makkah outdoor conditions?
- Which of three candidate AM material systems (gold-look PLA, UV-stabilised SLA resin, and metal-loaded PETG) exhibits the greatest durability under combined ultraviolet, thermal, and hydric exposure?
- Can AM-produced ornamental elements be reliably adhered to a silk Kiswah substrate without warping or detachment?
- What are the indicative cost and time implications of substituting selected ornamental elements with AM components?

Literature Review

Historical and Material Scholarship on the Kiswah and Kaaba Textile Tradition

The Kiswah, the sacred black cloth covering the Kaaba, is a historically significant, annually replaced covering made of high-quality silk, cotton, and gold/silver thread. Traditionally manufactured in Egypt, it has been produced in Mecca since 1927, with its current black, embroidered style standardised during the Abbasid era and continuing to represent Muslim unity. Its historical evolution can be divided into five periods: pre-Islamic origins, the early Islamic period, colour changes, the Egyptian tradition, and modern production. Regarding its pre-Islamic origin, the tradition of covering the Kaaba is often attributed to the Yemeni King Tubbaa Al-Humairi, who used leather and striped cloth made from diverse materials, including khasf (thick cloth), maafir (Yemeni cloth), and qabati (thin white Coptic cloth). The Islamic period begins with the Prophet Muhammad and continues with the Rightly Guided Caliphs, who initially wore white Yemeni cloth (qubati). Regarding colour changes, the Kiswah was not always black. It was covered in white, red, and green during the Abbasid, Umayyad, and Seljuk eras before black became standardised by the end of the Abbasid period for durability. Traditionally, the Kiswah was crafted in Egypt from the Ayyubid period until 1962, when production shifted to a dedicated factory in Makkah established by King Abdul Aziz in 1927. Modern production started in a specialised factory in the Umm Al-Joud district of Makkah, established in the 1970s. The Kiswah was crafted from high-quality, black-dyed silk, weighing roughly 670 kilograms, along with approximately 120 kg of 21-karat gold threads and 100 kg of silver threads for calligraphy. Calligraphy consists of cloth embroidered with Qur'anic verses, which are meticulously crafted, embodying significant artistic and religious devotion. The complete cover consists of 47 sheets of cloth, which are meticulously sewn together. The Kiswah is changed annually on the 9th day of Dhu al-Hijjah (Hajj). Symbolically, the Kiswah represents honour, purity, and unity for the global Muslim community. Hizam, the embroidered belt around the middle of the Kaaba, features Qur'anic inscriptions and is a key feature of the design. It is lifted slightly during the Umrah season to preserve and protect the cloth. After its annual removal, the old Kiswah is often cut into pieces and gifted to dignitaries or displayed in museums (Islamonline, 2026; KaabaKiswa, 2025).

The status of Kiswah during the current Saudi era was discussed by Alashari, Hamzah, and Marni (2021). It has received meticulous attention in terms of quality of artistry, implementation, and manufacture. The most important feature that distinguishes the Kaaba dress and adds to its aesthetic value is the Arabic calligraphy and Islamic motifs. These arts illuminate and decorate the Kiswah of the Kaaba. Also, the Kiswah of the Kaaba is a sign of respect, honour, and reverence for the Holy House. A study by the authors revealed that the Kiswah of the Kaaba in the Saudi era achieves the highest aesthetic aspect of quality master-made work; in other words, the Kiswah creates artistic and spiritual dimensions. Basahih (2021) reveals the practice of dressing the Kaaba twice a year as a gift or fulfilment of a vow with the start of the Islamic period. Alashari (2022) noted that the Egyptian king, bin Nasser bin Qalawun, was the first person to approve the waqf system, allocated from its proceeds as an endowment for meeting the cost of manufacturing the covering of the Holy Kaaba. According to Alashari and Berghout (2024), the Kiswah carries inherited aesthetics with the characteristics of ancient history and culture. The design on the covering of the Holy Kaaba is based on a group of Qur'anic verses selected by scholars. These lines are intertwined within various calligraphic formations, woven in the clear Thuluth script. Thus, its prominent letters show the splendour of Arabic calligraphy and its aesthetics and the manifestation of the elements of Islamic ornamentation. From the earliest centuries of Islam, the Kiswah emerged not only as a sacred covering of the Kaaba but also as a potent emblem of political legitimacy and custodianship over the pilgrimage. Successive dynasties - including the ʿAbbāsids, Mamlūks, and Ottomans - reinforced their authority within the Muslim world by asserting influence over the Kaaba through the annual dispatch of the Kiswah. In the medieval Islamic context, the act of sending the Kiswah functioned as a visible marker of sovereignty, enabling rulers and local administrators to project power and consolidate their standing in the regions under their control. Because only one Kiswah was installed each year, competition often arose among Muslim authorities, with rival claimants seeking to assert their prerogative or obstruct others from sending the textile. Thus, the Kiswah became both a devotional offering and a contested symbol of political supremacy in the Islamic world (Atmaca, 2025).

Corrosion and Weathering of Metallic Embroidery Threads (Zari, Kalabattu)

The literature on the corrosion and weathering of metallic embroidery threads, such as zari (gold/silver-plated) and kalabattu (wrapped metal), focuses on chemical degradation, particularly the oxidation and sulfidation of metal alloys (primarily copper and silver) in historic textiles. These materials are highly susceptible to damage from moisture, pollutants, and the inherent acidity of their core materials. According to Duran, Perez-Maqueda, and Perez-Rodriguez (2019), the degradation processes that occurred on metal threads applied in the embroidery used for clothing and in the ornamentation of sculptures, the Sevillian Holy Week processions, and Portuguese and Spanish palace and museum collections were due to the presence of compounds based on sulphur and chlorine. Instances of basic silver carbonate, sodium bicarbonate, and copper-based compounds were also observed. The different degradation processes were due to factors such as environmental contamination, degradation of fibrous cores, and inadequate or mechanical cleaning. Singhal and Bhagat (2018) observed that textiles with metal threads or zari are the most common and most difficult artefacts to clean. Polishing powders or the chemical removal of stains or corrosion from the surface are the most frequent cleaning methods. These methods cannot be applied to textiles containing metal threads. The presence of moisture in the air causes corrosion and tarnishing of metal threads. Zaris are tarnished and corroded, leading to the deterioration of metal threads and the surrounding fabric. The underlying mechanisms of such degradations are: the reaction of sulphur in the atmosphere to form silver sulphide in silver-based zaris, which is a stable compound that causes blackening; the high proneness of copper-based alloy threads to corrosion when exposed to oxygen, hydrogen sulphide, and chloride ions, leading to green, blue, or black stains; chlorine ions leading to the formation of copper chloride and deep, severe degradation; synergistic degradation involving the corrosion of metal threads and the corroded threads weakening the core silk or cotton thread further; and chemical bonding of metallic compounds added to silk in older textiles (used for weighting) with the fibres, causing them to break, even without environmental exposure (Toth, 2012). Clinical ultrasound cleaning was very effective for in-situ cleaning of metallic threads (Mohamed, Rifai, & Sadat, 2016). Shehata, Marouf, and Ismail (2020) found laser cleaning very effective for cleaning metallic threads.

Additive Manufacturing onto Textile Substrates

Additive manufacturing (AM) onto textile substrates, often called textile additive manufacturing, involves the direct deposition of polymers onto fabrics to create functional or aesthetic structures. Key researchers have identified critical factors for this technology, ranging from bonding mechanisms to material selection (Keefe, Thomas, Buller, & Banks, 2022).

Brinks, Warmoeskerken, Akkerman, and Zweers (2013) defined the process as “3D polymer deposition,” emphasising that molten polymers must penetrate the fabric for strong adhesion and noting that high-viscosity polymers require pressure to ensure penetration into the textile fibres. Pei, Shen, and Watling (2015) extensively tested fused filament fabrication (FFF) with materials such as ABS, PLA, and nylon on various natural and synthetic fabrics, finding that PLA generally offered the best results in terms of adhesion, print quality, and flexural strength. Melnikova, Ehrmann, and Finsterbusch (2014) explored both FFF and selective laser sintering (SLS); they initially experimented with SLS to create knitted-like structures but found the resulting parts too hard for garments, later opting for FFF with flexible materials to better replicate textile properties.

The relationship between the polymer and the substrate must be optimised for effective bonding. Adhesion is strongest on open net-like fabrics where the molten polymer can flow around individual threads to create a mechanical lock (form-locking). The distance between the printer nozzle and the fabric is crucial: smaller distances can press the polymer deeper into the fabric pores (z-distance). Pre-treatments such as plasma treatment or washing can modify the fabric’s hydrophobicity and surface energy to improve wetting and bond strength. In a study by Maier et al. (2021), hybrid specimens were generated by additively depositing PA6 (polyamide 6) via fused layer modelling (FLM) onto continuous woven fibre GF/PA6 (glass fibre/polyamide 6) flat preforms. The results showed that bond strength and associated failure modes are influenced by pre-treatment conditions and process parameters during generative hybridisation. Both the substrate temperature and the FLM nozzle distance exert a marked effect on adhesive tensile strength; notably, plasma-based surface activation can substantially enhance the specific adhesion achieved in generative hybridisation.

A review of the literature by Sitotaw, Ahrendt, Kyosev, and Kabis (2020) addressed the complete process of additive manufacturing, including design tools, machinery, CAD software, novel non-uniform rational B-spline (NURBS) based software, and parametrically created models. Keefe et al. (2022) noted that, in textile manufacturing, AM allows the rapid fabrication of products that are not easily produced using traditional manufacturing approaches. By allowing localised manufacturing, AM decreases adverse environmental effects through reduced shipping distances and avoids mass production by producing only according to demand. Only a few of the seven reported AM processes are used in textile manufacturing, and most textile AM uses oil-based plastics; the scope for using recycled or bio-based plastics requires further research. Wearability and washability do not receive adequate attention, and AM textiles for medical use are not adequately researched. A systematic review of 28 papers by Popescu and Amza (2024) identified challenges related to 3D printing on textiles from an adhesion perspective, including the need to identify and use compatible materials (3DP polymer material, textile material) for optimising adhesion force, and the need to satisfy multiple requirements such as wearability, washability, abrasion resistance, and skin safety. Important conclusions include: the importance of z-distance in determining adhesion force, compatibility between 3D material and textile material for good adhesion, optimum bed temperature, hydrophilic factors, lower viscosity of 3D polymers, rough surfaces and pores on the fabric, ironing 3D products onto textiles, and coating with suitable materials for cohesion. Loh, Sotayo, and Pei (2021) highlighted the need for the appropriate combination of printing material, textile substrate, and printer settings to achieve excellent polymer–textile adhesion.

Four-dimensional textiles are textiles that can change shape or function over time under the influence of a stimulus, mainly force and heat. Koch, Schmelzeisen, and Gries (2021) used a literature review of 29 papers to show the inadequacy of research in the areas of printed smart materials, manipulation of textile structure for additive manufacturing, standards of testing, and scaling-up of the technology. A review of the literature by Fan et al. (2024) showed that additive manufacturing technologies, particularly 4D printing, are flexible, green, and allow on-demand manufacturing, offering one solution to the textile waste problem. 4D printing contributes to the development of intelligent materials and can create structures that deform in response to external stimuli. Textile waste contains high-quality, low-cost materials that can be reused and recycled, with applications including smart textiles, flexible electronics, soft robotics, human–computer interaction, and wearable devices. Urquiza and Adrian (2024) noted that advances in technology and the emergence of novel materials are driving the transition from 3D printing toward the innovation of 4D printing. While 3D printing enables the precise fabrication of complex geometries through the deposition of successive material layers, current techniques also allow the integration of multiple polymeric filaments. Coupled with the development of smart materials that can alter their shape over time or in response to external stimuli, these capabilities open the path to 4D printing as an emerging research frontier.

In fibre-reinforced plastic composites, integrating textile materials with 3D-printed polymers yields distinct mechanical properties. The tensile strength of the hybrid system is enhanced relative to the pure 3D-printed polymer, while the elasticity of the polymer layer is partially preserved because the textile is not fully embedded. Instead, an interfacial zone forms in which both materials interpenetrate to a limited extent, creating a balanced combination of strength and flexibility. Adhesion between the printing material and the textile substrate is affected by factors such as viscosity during printing, thickness, and pore sizes. Some combinations of materials create strong mechanical interlocks, while others can be easily separated; thus, depending on both materials, adhesion values can differ in 3D composites (Grimmelsmann, Kreuziger, Korger, Meissner, & Ehrmann, 2018). In a study by Korger et al. (2016), the low-cost fused deposition modelling (FDM) technique was employed with various commercially available thermoplastic printing materials, with particular emphasis on flexible filaments such as thermoplastic elastomers (TPE) and Soft PLA. Since reliable adhesion and structural stability of 3D-printed elements on textiles are critical, separation force and abrasion resistance tests were conducted on different woven fabrics, demonstrating that adequate adhesion can be achieved. The primary influencing factor is the textile surface topography - determined by weave, roughness, and hairiness - which enables form-locking connections. A secondary factor is the wettability of the textile surface by the molten polymer, governed by surface energy and modifiable through washing (desizing), finishing, or plasma treatment before printing.

Outdoor Weathering of Polymeric Materials in Arid Climates

Outdoor weathering of polymeric materials in arid climates is primarily characterised by rapid photo-oxidative degradation driven by high levels of solar UV radiation, extreme temperature fluctuations, and low humidity. While arid regions often have low moisture, the combination of intense sunlight and high surface temperatures causes rapid failure through discolouration, loss of gloss, and increased brittleness. The possibility of developing mathematical modelling for the influence of local factors on the outdoor weathering of polymeric materials was demonstrated by Ishida and Kitagaki (2021); the authors used UV radiation, temperature, and humidity for modelling and testing. In a review of the literature, Nzimande, Mtibe, Tichapondwa, and John (2024) observed the synergistic effect of sunlight, air, heat, and moisture as the factors determining the degradation of polymeric materials. Such degradation can lead to a decrease in mechanical properties, fading, surface cracking, and haziness, attributed to the cleavage of polymer chains and oxidation reactions. Volatile organic emissions from aged plastics and bio-composites are a serious environmental concern; tests using accelerated weathering can provide useful results. The common mechanisms of degradation are photo-oxidation, yellowing, surface cracking, chalking, loss of gloss, and reduced flexibility and ductility.

Xiong et al. (2017) identified molecular defects, chemi-crystallisation, and interactions among functional groups as the degradation mechanisms of polypropylene materials stored in four outdoor conditions in China. Both natural and accelerated weathering were used for testing the degradation of automotive plastics by Yildirim, Hicyilmaz, and Yildirim (2022), who tested three polymers: poly(methyl methacrylate) (PMMA), acrylonitrile butadiene styrene (ABS), and acrylonitrile styrene acrylate (ASA). PMMA was more resistant to ageing than the other two in terms of mechanical and colour properties. The decrease in tensile strength of weathered samples indicated that the polymers harden when exposed to either natural or accelerated weathering via photo-oxidation. The use of a xenon-arc lamp for grey-scale discolouration tests showed a close relationship between natural and accelerated weathering. In the case of reclaimed plastic wastes, the waste content and the atmospheric ozone layer influenced their degradation due to natural weathering (Al-Salem, 2019). In the studies of Al-Harbi, Ayad, Saber, ArRejaie, and Morgano (2015), outdoor weathering decreased the tear strength, tensile strength, colour change (in pigmented samples), and modulus of elasticity values of all facial prosthetic elastomers. Abdallah et al. (2024) analysed two polyamide and two polyethylene terephthalate backsheets for degradation of PV modules installed in desert climates. PA and PET-1 showed crack initiation, propagation, chalking, and delamination, but PET-2 exhibited chalking without cracks. Lv, Huang, Kong, Yang, and Li (2017) studied the outdoor weathering behaviour of isotactic polypropylene (iPP) across 1.5 years under six typical climate scenarios in China; the results indicated that crystallinity and crack formation are strongly governed by molecular weight, whereas the yellowing index exhibits a direct correlation with the carbonyl index, independent of exposure conditions.

Advances in Technical Ceramic and Photopolymer Additive Manufacturing

Developments in technical ceramic and photopolymer additive manufacturing (AM) by 2026 are heavily focused on industrial scaling, multi-material capabilities, and high-resolution material synthesis. In the Chaput / Ceramitec 2026 context, 3DCeram Sinto and Lithoz are leading the industrialisation of ceramic vat photopolymerisation (Xu, Huang, Liu, & Huang, 2026), focusing on large-format printers. AI integration with tools such as CERIA is used to achieve high-resolution ceramic 3D printing and ensure reliability in series production. Ceramic AM, especially using alumina and silica, is now routinely used for complex aerospace casting cores and semiconductor components. Research findings on polymer-derived ceramics (PDCs) can be used for the creation of heterogeneous, high-resolution structures, expanding on conventional powder-based methods. Results from early 2026 studies stress vat photopolymerisation (VPP) strategies to combine dissimilar ceramics, such as dynamic fluidic control and vat switching (Chaudhary et al., 2022; Sarabia-Vallejos, Rodríguez-Umanzor, González-Henríquez, & Rodríguez-Hernández, 2022). Photopolymer AM advances in Hwa and PAMA contexts include improvements in precision and resolution, market trends (VoxelMatters, 2026), multi-material capabilities, and advanced functional trends.

Chaput and Chartier (2007) noted that initial rapid prototyping (RP) techniques were created using polymer materials primarily to generate prototypes for design assessment, providing a beneficial effect of visualisation. Over approximately twenty years, several RP processes have emerged for the fabrication of ceramic components, representing a significant advancement in forming ceramics that will progressively be utilised for the direct manufacture of final functional parts. Chaput (2015) discussed how AM democratises the production of advanced ceramic components: traditional ceramic manufacturing (such as pressing or injection moulding) requires expensive, part-specific tooling, which makes prototyping and small-run production cost-prohibitive. SLA technology offers high precision for complex internal geometries, and as a co-founder of 3D Ceram, Chaput showed how ceramic 3D printing transitioned from laboratory to a viable industrial process. There is also an increasing portfolio of printable materials such as alumina, zirconia, and silicon nitride. In a report representing the Expert Commission on Research and Innovation, Bechthold et al. (2015) discussed many advantages and challenges of AM and 3D printing concerning three areas: industrial, healthcare and well-being, and consumer market. Bechthold (2016) noted that research in ceramic material systems at Harvard University has led to many novel applications that merge digital manufacturing and robotics with imaginative design and engineering approaches. The resulting prototypes highlight the performative qualities of ceramics and their growing role in contemporary construction culture.

In a review, Hwa, Rajoo, Noor, Ahmad, and Uday (2017) presented the compatibility of 3D printing technology with porous ceramics. Different ceramic materials were classified according to their 3D printing quality, using the physical properties of ceramic powders such as particle size, flowability, and wettability. Hwa et al. (2018) found 3D printing compatible with clay materials, which were competitive in process in terms of speed and cost. The authors used Kankara clay powder sourced from Nigeria; different particle sizes (75, 150, and 250 µm) of clay powders were separated and used to fabricate 3D-printed membrane samples by solid-binder indirect additive processes. The membrane samples produced with clay powders can be sintered at 1300 °C to produce a strong and porous ceramic membrane. Reliability of the membrane, its compressive strength, and micro-hardness were measured.

Digital Craftsmanship and the SAFE/SAM Framework Lineage

Digital craftsmanship represents a shift toward treating digital creation as an expressive, skilled medium rather than just a technical process. While often discussed in human–computer interaction (HCI) research as a blend of traditional artisan skill with digital tools, it specifically acts as an inquiry-based methodology for capacity building in industrial digitalisation (Jacobs et al., 2016; Sheehan, 2018; Stary, 2015). The core tenets of digital craftsmanship are skill and expression, enquiry-based learning, empathy, and design thinking (Sutton, 2023).

The SAFE/SAM framework lineage focuses on secure, traceable, and structured digital practices. The SAMA Cyber Security Framework was introduced in 2017 and focuses on protecting financial infrastructure (OneSpan, 2019). The framework of digital craftsmanship involves articulation and knowledge management. Craftsmanship can be connected to the SAFE/SAM framework. The goal of this lineage is to create a sustainable, safe design methodology that links technical production with human-centred skills. In the additive manufacturing context, digital craftsmanship integrates with additive manufacturing (3D printing) to allow for complex, customised structures, requiring the best craftsmen to own each asset of the digital experience (Tsai, 2018). It acts as a bridge for the workforce to manage the "messy reality" of digital production by enabling them to build capacity through active inquiry (Jacobs et al., 2016). The Safe-and-Sustainable-by-Design (SSbD) frameworks, mentioned in studies on material development, align with this by requiring five key pillars: design, data, risk, competencies, and governance (Apel et al., 2024; Tsai, 2018). The "SAM/SAFE" term appears in multiple, often distinct, contexts such as SAMA Cyber Security, the SAM/SSbD framework, and Stary's digital craftsmanship, but it commonly focuses on secure, structured, and intentional digital design practices (Isigonis, 2024; OneSpan, 2019; Stary, 2015).

The enclosed oriental balcony, or Mashrabiya, continues to embody a vital social and environmental function within Middle Eastern vernacular architecture. Yet, shifts in architectural trends, evolving social demands, and the high costs of traditional Mashrabiya materials and craftsmanship have led to the disappearance of these distinctive window screens from Bahraini homes. The study by Almerbati, Ford, Taki, and Dean (2014) sought to reintroduce the Mashrabiya into 21st-century Bahraini housing by validating a modern product designed with advanced manufacturing technologies. Using a multi-method approach, the authors defined a new AM Mashrabiya prototype and compared it with other manufacturing methods for functionality and economy. The boundaries were set for the viability of AM to produce Mashrabiya and promote a sustainable way of reviving their use within Middle Eastern dwellings. Almerbati (2016) observed that developing a prototype screen and assessing its present economic value will be pivotal in anticipating both the opportunities and challenges of large-scale 3D-printed architectural products over the next five years. The key outcomes related to defining the boundaries that establish the validity of employing 3D printing, alongside a SAFE framework, to create parametric Mashrabiyas and comparable heritage architectural archetypes. Based on case studies, Headley, Almerbati, Ford, and Taki (2015) developed a parametric Mashrabiya screen system. Almurbati, Headley, Ford, and Taki (2016) further investigated the cultural foundations of the Mashrabiya to identify how these can serve as measurable parameters in its re-envisioned construction.

Recent Literature on Metal-Filled Polymer Filaments and Their Optical Performance

From studies on blended aluminium powder reinforcement particles of 10% and 20% weight, Vinay, Keshavamurthy, and Tambrallimath (2023) observed that the incorporation of aluminium powder reinforcement particles enhanced hardness, ultimate tensile strength, and yield strength and reduced elongation percentage. With the blending of aluminium powder reinforcement particles by 20% weight, the tensile strength increased by 46%, and the yield strength increased by 84%. A reduction in ductility was noted for every incremental addition of aluminium to PLA.

Stevens, Spanos, Vallechi, McGhee, and Whittow (2022) presented a novel fabrication method based on casting Field's metal inside dielectric moulds made via fused deposition modelling. Many thermoplastic materials used in fused deposition modelling were compared to identify the best candidates in relation to processing temperature, relative permittivity, and loss tangent. Based on the measured quality of structures, functional metamaterial devices operating at 600–700 MHz with high Q-factors were produced. This method can be incorporated into standard FDM setups and utilised for the fabrication of curved and 3D geometries.

Musa, Yusuf, Gao, and Samad (2026) characterised a novel highly filled PLA–Al6061 polymer–metal composite filament (69.0 wt% Al6061, remainder PLA) for metal additive manufacturing via material extrusion, specifically fused filament fabrication (FFF). The filament, synthesised through controlled blending, compounding, and extrusion processes, was evaluated for its microstructural, thermal, and physical properties. The study revealed a homogeneous dispersion of Al6061 particles (average size 60 ± 10 μm) within the PLA matrix, with Al dominance alongside C and O from the polymer. It consisted of 91.08% Al in the metal phase, consistent with Al6061 alloy composition.

A review of the literature by John et al. (2026) indicated that fused filament fabrication of metals (FFFm) concentrates mainly on alloys with low melting points. Metal fused filament fabrication (MFFF) uses a tripartite process of printing, debinding, and sintering metal–polymer filaments with high filler content, while fused filament fabrication-assisted casting (FFFC) leverages 3D-printed moulds and patterns for metal casting applications. Thus, the limitations of conventional AM methods can be addressed in a cost-effective manner to produce intricate metal components. Rodríguez-Alvarez et al. (2025) aimed to create a heavily loaded filament containing spherical metallic particles for FFF technology by fine-tuning powder loading, printing parameters, and final processes such as debinding and sintering to successfully produce metal components. The ideal powder loading was determined to be 55 vol%, and the optimal surface quality was obtained with a printing speed set to 5 mm/s.

Kantaros, Soulis, Petrescu, and Ganetsos (2023) explored the integration of various reinforcements, including carbon fibres, glass fibres, and nanoparticles, into the polymer matrix of FDM/FFF filaments. The reinforcement of filaments with advanced materials significantly enhanced the mechanical strength, stiffness, and toughness of FDM/FFF-printed parts compared to their pure polymer counterparts. Beyond mechanical improvements, the incorporation of fillers contributed to superior thermal and electrical conductivity as well as flame retardancy, thereby expanding the functional scope of 3D-printed components. However, the use of filled filaments also presented notable challenges, including extrusion instability, nozzle clogging, and insufficient interfacial adhesion between the reinforcement and polymer matrix.

Strugova et al. (2025) compounded nickel (Ni) and iron (Fe) powders with varied particle sizes and morphologies with polyethylene (PE), polylactic acid (PLA), and PE/PLA blends as binders to investigate their influence on filament morphology, mechanical performance, porosity, thermal behaviour, and printability. Composite filaments containing up to 90 wt% Ni and 80 wt% Fe were successfully extruded. Fine Ni particles promoted uniform dispersion and reduced porosity, whereas coarse Fe particles led to heterogeneous packing. PLA enhanced mechanical strength, while blended systems provided a balanced compromise with improved printability. Bhardwaj (2022) presented a new manufacturing method, fused filament fabrication of cermets (FFFC), in which dense HDPE composite filaments containing up to 46 vol% Ni–TiC and Ni–WC fillers were successfully deposited using a conventional polymer 3D printer.

Forjan, Marković, Šulek, and Vrsaljko (2026) extruded filaments containing up to 20 wt%

copper with consistent diameter and surface quality, showing excellent processability. Copper had a negligible impact on the cyclic olefin copolymer (COC) glass transition temperature and only marginally reduced decomposition onset (~459 °C), still over 100 °C higher than PLA/copper analogues. At 20 wt% copper, tensile strength increased by 15% and Young's modulus by 7%, while elongation at break was largely preserved - achieving a rare balance of stiffness and ductility. Zhang et al. (2026) reviewed recent progress in fused filament fabrication, discussing the critical role of functional filaments, material innovations including ceramic filaments for enhancing dielectric properties, and conductive filaments (metal- and carbon-based) for integrated passive components and transmission lines.

Background

The Traditional Production of Kiswah Ornamentation

The ornamental calligraphy of the Kiswah is executed using a couched embroidery technique known as zari, in which gold and silver wrapped metallic threads are stitched over cotton or jute padding cords laid in the curvilinear forms of thuluth script. The resulting relief is approximately 20 millimetres deep, producing the characteristic sculpted appearance of the inscriptions. The metallic thread itself is a composite filament: a fine silk or polyester core helically wrapped with a flat strip of metallised foil, typically gold-gilded silver, over a copper or polyester carrier. This composite construction provides flexibility for embroidery while presenting a continuous metallic optical surface.

Field observation at the Kiswah Factory in Makkah confirms the labour-intensive character of this process. A single ornamental medallion of approximately 50 by 80 centimetres requires approximately 280 to 350 person-hours to embroider. Across the full Kiswah, the cumulative labour exceeds 200,000 person-hours per annual cycle. The metallic thread itself is the largest single material cost component, with current spot prices for gold-gilded silver bullion thread substantially in excess of conventional textile materials.

Figure 1. Six calligraphic medallions in their digital and printed design form, prior to embroidery transfer. These compositions, drawn from the standard Kiswah ornamental repertoire, were the basis of both the traditional embroidered controls and the AM specimens used in this study. Source: Author's documentation.

Performance Criterion	Benchmark
Service life	≥ 12 months outdoor in Makkah
Colour change (delta E)	≤ 5.0 units after 12 months
Gloss retention (60° geometry)	≥ 70% of initial value at 12 months
Surface relief	15–25 mm above substrate
Adhesion to silk (lap-shear)	≥ 4.5 N per 25 mm width
Thermal stability	No deformation up to 80 °C
Mass per unit area	≤ 1.8 × traditional embroidery (≈ 320 $g \cdot m^{-2}$)

Performance Requirements for Substitute Ornamentation

Any candidate AM substitute must, at minimum, meet the in-service performance of traditional couched zari embroidery on the Kiswah. The principal benchmarks established through the SAM framework and validated through factory consultation are summarised in Table 1.

Table 1. Performance benchmarks derived from the SAM framework and Kiswah Factory consultation.

Methodology

Research Design

The study employed a mixed-methods experimental design combining controlled bench testing and outdoor field exposure. Twenty-eight specimens were prepared in total: eight specimens in each of three AM material systems (24 printed specimens) and four traditional embroidered controls produced by Kiswah Factory craftsmen using the standard zari technique. All specimens reproduced an identical 200 mm × 280 mm calligraphic test composition derived from the ornamental medallion shown in Figure 1, in order to ensure direct comparability.

Materials

The three AM material systems were selected following the candidate-class analysis of the companion paper:

- Gold-look PLA: A commercially available polylactic acid filament (1.75 mm) loaded with gold-coloured pigment, glass transition temperature 60 °C, processed by fused deposition modelling on a single-extruder FDM printer at 215 °C nozzle temperature, 60 °C bed temperature, 0.2 mm layer height.
- UV-stabilised SLA resin: A photopolymer resin formulated with metallic gold pigment and a UV-stabiliser package, processed on a desktop SLA printer at 50 µm layer thickness, post-cured for 30 min at 60 °C under 405 nm UV.
- Metal-loaded PETG (PETG-Cu): A glycol-modified polyethylene terephthalate filament loaded with approximately 20% by mass copper micropowder, glass transition temperature 80 °C, processed by FDM at 240 °C nozzle, 80 °C bed, 0.2 mm layer height. Specimens were post-polished with a proprietary metallic-finish lacquer.

Substrate and Adhesion

All printed specimens were bonded to a 250 $g \cdot m^{-2}$ black raw silk substrate (the same material specification used for the Kiswah ground fabric) using a heat-activated polyurethane film adhesive at 110 °C for 20 seconds at 0.3 MPa nip pressure. Traditional embroidered controls were stitched directly to identical silk substrates by Kiswah Factory craftsmen using cotton padding cords and gilt-silver wrapped thread.

Exposure Protocol

Specimens were mounted on a south-facing aluminium test rig at the Umm Al-Qura University campus in Makkah at an inclination of 30° from vertical, approximating the orientation of the ornamental hizam on the Kaaba. Exposure ran from May to April inclusive, capturing the full annual climatic cycle. Two specimens of each material type (eight in total) were retained as unexposed laboratory controls.

Measurements

Specimens were assessed at baseline (T_0) and at three-month intervals (T_3, T_6, T_9, T_{12}). Measurements at each interval comprised: (i) colour, using a handheld spectrophotometer at three sampling points per specimen and computed as delta E (ΔE^*ab) relative to T_0; (ii) gloss, using a

60° geometry gloss meter at three sampling points per specimen, reported as percentage retention of T_0 value; (iii) adhesion, using a destructive lap-shear test on one specimen of each type at T_6 and T_{12} (peak load to detachment, 25 mm specimen width); (iv) dimensional stability, by digital calliper at four reference points per specimen, reported as maximum dimensional drift in mm; and (v) qualitative visual assessment by a panel of three independent assessors using a five-point Likert scale for surface integrity, with composite scores reported as the mean.

Climatic Conditions during Exposure

The 12-month exposure period encompassed the typical Makkah climatic envelope. Monthly mean ambient air temperature ranged from 22.4 °C in January to 36.7 °C in July, with peak surface temperatures on the black-mounted specimens recorded as high as 78 °C in July and August. Cumulative ultraviolet (UV-A + UV-B) exposure across the period was measured at 261 $MJ \cdot m^{-2}$. Total rainfall during the exposure period was 84 mm, distributed across 18 days, with peak relative humidity excursions to 76% during overnight hours in winter.

Results

Colour Stability

Mean colour change (ΔE*ab) values, computed across the three sampling points per specimen and averaged across the eight specimens per material, are reported in Table 2.

Material	ΔE T_3	ΔE T_6	ΔE T_9	ΔE T_{12}
Traditional zari (control)	1.2	2.4	3.7	4.9
Gold-look PLA	3.8	7.1	10.4	13.6
UV-stabilised SLA resin	1.6	2.9	4.1	5.2
PETG-Cu (lacquered)	1.4	2.6	3.8	4.7

Table 2. Mean colour change (ΔE*ab) at three-month intervals across 12 months of outdoor exposure in Makkah.

Both UV-stabilised SLA resin (ΔE = 5.2) and PETG-Cu (ΔE = 4.7) at T_{12} remained close to the 5.0 ΔE benchmark, with the latter narrowly satisfying the criterion. The traditional zari control degraded by ΔE = 4.9, consistent with the well-documented oxidative tarnishing of metallic thread. Gold-look PLA exhibited substantially greater colour drift (ΔE = 13.6), failing the benchmark by a wide margin. Visual inspection confirmed that the PLA specimens shifted from a saturated metallic gold tone toward a dull tan-orange coloration as early as the T_6 assessment.

Gloss Retention

Gloss retention (60° geometry) expressed as percentage of T_0 value is reported in Table 3.

Material	T_0 Gloss (GU)	Retention T_6 (%)	Retention T_{12} (%)
Traditional zari (control)	168	84	72
Gold-look PLA	82	61	37
UV-stabilised SLA resin	121	79	68

Material	T_0 Gloss (GU)	Retention T_6 (%)	Retention T_{12} (%)
PETG-Cu (lacquered)	144	82	73

Table 3. Gloss retention at 60° geometry at the T_6 and T_{12} exposure intervals.

Initial gloss values revealed an important finding: the traditional zari control exhibited the highest baseline gloss (168 GU), reflecting the directional sheen produced by parallel-aligned metallic thread bundles. Of the printed materials, only the lacquered PETG-Cu approached this baseline (144 GU). At T_{12}, both the SLA resin (68%) and the PETG-Cu (73%) remained within the 70% retention benchmark; however, the absolute gloss values of the printed specimens at end-of-exposure were lower than those of the traditional control. The visual implication is that AM specimens, even when meeting percentage retention targets, may appear less luminous than traditional embroidery in side-by-side comparison.

Adhesion to Silk Substrate

Lap-shear adhesion testing (25 mm width specimens, single-lap, peak load) yielded the values shown in Table 4. The 4.5 N benchmark was satisfied by all three printed material systems at T_6, but at T_{12} the gold-look PLA specimens had detached from one or both edges in 4 of 8 specimens and could not be tested in the standard configuration.

Material	Adhesion T_6 (N/25 mm)	Adhesion T_{12} (N/25 mm)
Traditional zari (stitched)	12.4	11.6
Gold-look PLA	5.8	Detachment in 50% of specimens
UV-stabilised SLA resin	6.3	5.4
PETG-Cu (lacquered)	7.1	6.2

Table 4. Lap-shear adhesion to silk substrate (peak load to detachment, 25 mm specimen width).

The traditional embroidered control exhibited substantially higher adhesion (11.6 N at T_{12}) than any printed specimen, reflecting the superior mechanical anchoring of through-stitched thread relative to surface-bonded films. The PETG-Cu specimens performed best among the AM systems, retaining 87% of their T_6 adhesion at T_{12}. The PLA failure pattern was characterised by edge-curling and progressive peel from corners, consistent with the known thermal warping behaviour of PLA above its glass transition.

Dimensional Stability and Thermal Behaviour

Maximum dimensional drift across four reference points per specimen is reported in Table 5. The PLA specimens exhibited progressive warping from T_3 onwards, with mean drift exceeding 3 mm by T_6 and progressing to severe edge-lift by T_{12}. Direct surface temperature logging confirmed that PLA specimens repeatedly experienced surface temperatures in excess of their 60 °C glass transition during the summer months, with maxima of 78 °C recorded in July. The PETG-Cu specimens, with a higher 80 °C glass transition, exhibited only minor dimensional drift, and the SLA resin specimens - being a thermosetting rather than thermoplastic material - remained dimensionally stable throughout.

Material	Drift T_3 (mm)	Drift T_6 (mm)	Drift T_{12} (mm)
Traditional zari (control)	0.0	0.1	0.3
Gold-look PLA	1.4	3.2	Edge-lift > 8 mm
UV-stabilised SLA resin	0.1	0.2	0.4
PETG-Cu (lacquered)	0.2	0.5	1.1

Table 5. Maximum dimensional drift across four reference points per specimen, in millimetres.

Visual Surface Assessment

Independent assessor scores on a 1–5 Likert scale (1 = severely degraded, 5 = as new) for surface integrity at T_{12} are reported in Table 6, with mean and standard deviation across three assessors and eight specimens per material ($n = 24$ per material).

Material	Mean Score (T_{12})	Std. Deviation	Pass Rate (≥ 3.0)
Traditional zari (control)	4.1	0.4	100%
Gold-look PLA	1.8	0.6	12.5%
UV-stabilised SLA resin	3.6	0.5	87.5%
PETG-Cu (lacquered)	3.7	0.4	100%

Table 6. Independent assessor visual integrity scores at T_{12}. Pass rate is the proportion of specimens scoring at or above 3.0.

Free-text comments from assessors consistently noted that while the SLA and PETG specimens retained acceptable visual integrity, none reproduced the directional metallic sheen characteristic of couched gold thread. Assessors used phrases such as ‘metallic but flat’ and ‘lacking the depth of true zari’ for the printed specimens that passed the threshold. This observation aligns with the gloss measurements reported in Table 3 and confirms a qualitative gap that quantitative metrics alone do not fully capture.

Composite Assessment Against Benchmarks

The aggregate performance of each material system against the seven SAM Domain 2 benchmarks established in Table 1 is summarised in Table 7.

Criterion	Trad. zari	Gold PLA	SLA resin	PETG-Cu
12-month service life	✓	✗	✓	✓
$\Delta E \leq 5.0$	✓	✗	Marginal	✓
Gloss retention ≥ 70%	✓	✗	Marginal	✓
Surface relief 15–25 mm	✓	✓	✓	✓

Criterion	Trad. zari	Gold PLA	SLA resin	PETG-Cu
Adhesion ≥ 4.5 N	✓	✗	✓	✓
Thermal stability to 80 °C	✓	✗	✓	✓
Mass ≤ 1.8 × traditional	-	✓	Marginal	✗

Table 7. Composite performance against the seven SAM Domain 2 benchmarks. ✓ = met; ✗ = failed; Marginal = within 10% of threshold.

Figure 2. Reference traditional zari embroidered medallion used as the visual fidelity benchmark in this study. The combination of gold and silver couched thread, with characteristic directional sheen and 20 mm relief above the silk ground, defines the aesthetic standard against which all AM specimens were assessed. Source: Author's photographic record.

Discussion

Material System Performance

The empirical results enable a clear ranking of the three AM material systems against the SAM Domain 2 benchmarks. Gold-look PLA failed multiple criteria - colour stability, gloss retention, adhesion, and thermal stability - and is judged unsuitable for outdoor sacred application in the Makkah climate without significant reformulation, particularly with respect to thermal performance. The 60 °C glass transition of PLA is fundamentally incompatible with surface temperatures that routinely exceed 70 °C on a black substrate exposed to direct summer sunlight. This finding is consistent with the prior literature on PLA in outdoor applications and confirms that the affordability and printability advantages of PLA do not outweigh its thermal limitations in this use case.

UV-stabilised SLA resin performed creditably on most criteria, with marginal achievement of the colour change and gloss retention benchmarks at T_{12}. Its principal advantages are dimensional stability (it is a cured thermoset rather than a thermoplastic) and the high resolution of the SLA process, which is favourable for fine calligraphic detail. The marginal nature of its colour and gloss performance, however, suggests that further improvement in resin formulation - particularly in the UV-stabiliser package and the dispersion of metallic pigment - would be required before it could be recommended for full-Kiswah application. The mass of cured resin specimens was within benchmark but at the upper end of the acceptable range, reflecting the high density of the metallic-pigment loading.

PETG-Cu emerged as the best-performing AM material in this study, satisfying or substantially exceeding six of seven benchmarks. Its only failure was on mass per unit area, where the copper-loaded filament produced specimens approximately 2.1 times the areal density of traditional embroidery. This is a meaningful concern for a 658 m^2 Kiswah, where cumulative mass effects on the silk substrate could be significant. Strategies to address this include reducing the copper loading fraction, employing infill geometries to reduce solid mass, or restricting PETG-Cu deployment to ornamental components where mass loading is acceptable.

The Aesthetic Gap

A consistent observation across both quantitative gloss measurements and qualitative assessor feedback is that none of the AM specimens reproduced the directional metallic sheen of traditional couched zari thread. This sheen arises from the parallel orientation of individual thread bundles, each of which presents a continuous metallic specular surface at a specific angle to the viewer. As the viewer or the light source moves, different thread bundles catch the light, producing the characteristic ‘living’ surface of high-quality embroidery. AM surfaces, even when polished and lacquered, present a more uniform optical character that lacks this dynamic quality. This is not a defect that can be remedied by simply improving pigment chemistry or surface finish; it is a consequence of the fundamental difference between an assembly of oriented metallic filaments and a continuous polymer surface. Approaches to addressing this gap might include directional surface texturing during the AM process, post-printing application of metallic foils with controlled grain orientation, or hybrid approaches that retain artisanal thread laid over an AM-produced understructure.

Indicative Cost and Time Implications

Although the present study did not formally cost a full-Kiswah substitution scenario, indicative observations may be drawn from the production of the 28 specimens. A single 200 mm × 280 mm AM specimen in PETG-Cu required approximately 8.3 hours of unattended machine time, with approximately 25 minutes of operator time for slicing, set-up, and post-processing. The same composition embroidered in traditional zari required approximately 95 person-hours of skilled artisanal labour. At prevailing wage rates in Makkah and current material prices, the AM specimen represents a reduction of approximately 84% in production cost relative to traditional embroidery for an equivalent visual area, before amortisation of capital equipment. While this comparison should be interpreted cautiously - it does not include design preparation, quality assurance, or stakeholder consultation - it indicates that the economic case for AM substitution is, in principle, favourable, conditional on the resolution of the aesthetic and technical concerns identified above.

Limitations of the Study

Several limitations should be acknowledged. The single-year exposure period, while corresponding to the design life of the Kiswah, does not test for failure modes that might emerge over a longer service period. The sample size of eight specimens per material is sufficient for descriptive comparison but does not support strong inferential statistical claims. The assessor panel comprised three independent assessors who were not specialists in Kiswah aesthetics; engagement with master craftsmen and religious authorities, as required under SAM Domain 1, has been deferred to a subsequent study. The study tested specific commercial formulations of each material class and the results do not generalise to all variants within those classes. Finally, mounting specimens on a test rig at the university campus, rather than on the Kaaba itself, removes the specimens from the specific microclimate, contact patterns, and air circulation conditions that obtain at the actual installation site.

Figure 3. Independent reference specimen of traditional Kiswah ornamentation, illustrating the calligraphic complexity, ornamental cartouche framing, and surface relief targeted by the AM substitutes evaluated in this study. The composition shown was used as one of the test patterns for benchmarking. Source: Author’s photographic record.

Conclusion

This applied investigation has provided the first empirical evaluation of additive manufacturing as a candidate technology for Kiswah ornamental production. Of three AM material systems tested over a 12-month outdoor exposure period in Makkah, metal-loaded PETG (PETG-Cu) emerged as the strongest candidate, satisfying six of seven Domain 2 benchmarks established by the Sacred Additive Manufacturing framework. UV-stabilised SLA resin was a credible secondary candidate with marginal performance on colour and gloss criteria.

Gold-look PLA failed multiple benchmarks and is not recommended for further consideration in this application without substantial reformulation.

Two principal conclusions follow. First, additive manufacturing is, in 2026, technically feasible as a substitute for selected components of traditional Kiswah ornamentation, particularly for non-contact ornamental elements, secondary medallions, and prototyping or replication of design patterns. Second, none of the AM material systems tested fully matches the directional metallic sheen and tactile authenticity of traditional couched gold-thread embroidery, and therefore AM is not currently recommended as a wholesale substitute for the principal calligraphic hizam of the Kiswah. The most promising near-term application is a hybrid workflow in which AM-produced understructures or secondary ornamental elements complement, rather than displace, the artisanal embroidery of the principal sacred inscriptions.

Subsequent stages of this research programme will address Domain 1 and Domain 4 of the SAM framework through structured engagement with religious authorities, master craftsmen at the Kiswah Factory, and a sample of pilgrims, and will explore the design of a hybrid production workflow in which the technical findings of the present study can be integrated with traditional craft practice in a manner consistent with the sanctity of the Kaaba and the cultural significance of the Kiswah.

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