17 (2023) 200129

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

The potential of converting plastic waste to 3D printed products in Sub-Saharan Africa

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ARTICLE INFO

Keywords:
3D printing
Additive manufacturing
Recycling
Distributed manufacturing
Waste management
SDGs

ABSTRACT

Additive manufacturing (3D printing) can transform low-income societies with underdeveloped infrastructure and inadequate manufacturing capabilities. However, uptake in sub-Saharan Africa is still very low. This study adopted a transdisciplinary approach which included critical synthesis of the extant literature, laboratory experiment and a cross sectional engagement with stakeholders, to examine the potential of converting plastic waste to 3D printed products in sub-Saharan Africa. The study showed that while several extruders have been developed in the last decade, there are still many challenges some of which include difficulty to produce filaments with consistent diameter, degraded mechanical properties and health hazards from emissions during extrusion. Furthermore, it was observed that communities across sub-Saharan Africa are interested in 3D printing but do not have sufficient understanding. The study highlights the need for building local capacity to develop, operate and maintain technologies associated with 3D printing.

1. Introduction

Plastics have desirable properties, versatility, low cost, and low weight (Mwanza and Mbohwa, 2017). They have produced a wide range of products across virtually every sector over the last 50 years (Zhong and Pearce, 2018). Since the discovery of polystyrene in 1839, there has been an exponential increase in plastic types, including; polyethene terephthalate (PET), polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS) and polypropylene (PP), amongst others. As of 2015, there were over 8.3 billion tonnes of plastic products and around 6.3 billion tonnes of plastic waste had been generated (Geyer et al., 2017). The situation is exacerbated by the fact that only 9% of global plastic production was recycled while 79% was disposed of in landfills and the oceans (Geyer et al., 2017). Recent projections show that if the demand for plastic products remains high by 2050, 26 billion tons of plastic waste will have been produced, half of which will be dumped in landfills or the environment (Geyer et al., 2017).

The proliferation of plastics combined with inadequate end-of-life waste management practices has resulted in plastic pollution being one of the biggest challenges of the 21st century. This has led to significant environmental and health problems (Wabnitz and Nichols, 2010) that are increasingly intractable (Ryberg et al., 2019; Thompson et al., 2009; Wabnitz and Nichols, 2010). Studies show that around 5–13 million tonnes of discarded plastics end up in the oceans annually (Jambeck et al., 2015), impacting marine fauna and wildlife, causing death and severe injury (Kühn et al., 2015). Moreover, plastic pollution can also significantly affect humans as they contain toxic additives and harmful chemicals that the human body can absorb through food, air, and water. This potentially causes serious health problems. In addition, studies (Eerkes-Medrano et al., 2019; Royer et al., 2018; Wright and Kelly, 2017) have shown that plastics release methane and ethylene when exposed to sunlight, thereby contributing to greenhouse gas emissions.

Even though recycling has been recognised as the most established environmentally friendly plastic waste management strategy (Hopewell et al., 2009; Zhong and Pearce, 2018), recycling of plastics remains very low. For instance, in 2018, Europe produced 61.8 million tonnes of

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https://doi.org/10.1016/j.rcradv.2023.200129

plastic, and recycled only 32.5% of this (Plastics Europe, 2018). One challenge related to plastic recycling is that it is not always economically viable (Kreiger et al., 2014; Santander et al., 2020). Plastics are usually recycled through centralised networks to benefit from economies of scale in the production of low-value products (Kreiger et al., 2014; Santander et al., 2020). A significant drawback of this centralised approach is that it can be quite expensive to transport these high volume and low weight polymers (Kreiger et al., 2014; Santander et al., 2020). Additionally, traditional recycling can have a significant environmental pollution impact (Ragaert et al., 2017) due to the greenhouse gas emissions associated with collecting and transporting the waste materials (Garmulewicz et al., 2016). Recycling rates are even lower in low- and middle-income countries due to various issues such as inadequate infrastructure and social factors (Oyinlola et al., 2018). Furthermore, environmental concerns are usually not a priority as the majority of the population are still struggling to meet the necessities of life, such as food and shelter (Kolade et al., 2022b; Oyinlola et al., 2022). Adefila et al. (2020) suggested that community members could be incentivised to develop sustainable waste management practices by adding value to the waste stream. This has been demonstrated in various sectors such as buildings (Kim et al., 2019; Oyinlola and Whitehead, 2019) Arts and crafts (Babaremu et al., 2022; Wagner-Lawlor, 2018) and filaments for additive manufacturing (Mikula et al., 2021).

This paper adopts a transdisciplinary approach to evaluate the potential of converting plastic waste to filaments for 3D printing in Sub-Saharan Africa. Firstly, a critical review of the literature is conducted to establish the state of the art of converting plastic wastes to filaments. Secondly, experimental tests are conducted to determine the suitability of various available conversion devices (extruders), as well as the viability of using the resulting filaments for local products. Thirdly, a cross sectional engagement with stakeholders in sub-Saharan Africa is conducted to characterise the socio-cultural factors affecting the uptake of the process. Successfully converting plastic waste to filaments has significant implications for the adoption and success of additive manufacturing (3D-Printing), in sub-Saharan Africa as it provides the opportunity for plastic waste to be turned into new, more valuable products. This will be a game changing disruption to manufacturing as 3D printing technology has been used to fabricate a wide range of products, from pre-production models and temporary parts, to end-use products in aerospace, dentistry, medical implantation, automotive and even fashion design (Celik, 2020). Furthermore, this approach will make positive contributions to achieving several targets of the Sustainable Development Goals (SDGs), including Decent work and economic growth, (SDG 8), Industry, Innovation and Infrastructure (SDG 9), sustainable and inclusive communities (SDG 11) and sustainable consumption and production (SDG 12).

2. Methodology

The study adopted a mixed methods approach, drawing on a critical synthesis of the extant literature, laboratory experiments, along with engagements with a range of stakeholders.

2.1. Literature review

A critical review of peer-reviewed academic literature on converting plastic to filaments, supplemented by grey literature, including newspaper articles and national policy reports, was conducted using Scopus, Web of Science, Google Scholar, and Google search engine. The academic literature search involved the use of various terms, including: "Polymer extruder", "Recycled filament", "Plastic extrusion", “Low-resource settings”, “Recyclable waste”, “Additive manufacturing", "3D printing", “Low-cost recycling”, amongst others. This was further supplemented with information from manufactures websites. This review provided insights on the state of the art with regards to converting plastic waste to filaments, especially in low-income settings.

2.2. Experimental analysis

2.2.1. Extruders

In order to establish the viability of producing filaments in low-income settings using commercially available extruders, three extruders were purchased. Fig. 1 shows a picture of one of the extruders. Extensive experiments were conducted in the laboratory, using the most promising one of them - Noztek pro. PLA and XT (carbon fibre composite pellets) were purchased from Colorfabb (ColorFab, 2020) and used as feedstock for the extrusion process. The ambient and extrusion temperatures and resultant filament diameter were recorded every minute during each experiment. After each test, the mass of filament produced was measured with a mass balance to calculate approximate extrusion rates under the different tests.

2.2.2. Filaments

Commercial filaments made from recycled plastics were purchased and tested against the ethical filament standards. For each commercial filament tested, 6 m was cut from the end of the roll, excluding the end that was secured to the spool. The filament diameter was measured every 100 mm (±10 mm maximum) using digital callipers. Each diameter measurement was taken in at least 2 directions to check for roundness of the filament. Filaments of 1.75 mm and 2.85 mm in diameter were tested and compared to a high-quality standard of 1.75 ± 0.05 mm/2.85 ± 0.10 mm and the Ethical Filament standard of 1.60–1.85 mm/2.75–3.25 mm. A total of 11 different filaments were tested.

Only one of the filaments purchased (Tech for Trade), was specifically produced for low – income settings (and produced in a low income setting). Therefore, tensile tests were conducted on coupons made from the Tech for Trade filament as illustrated in Fig. 2.

2.3. Stakeholder engagement

2.3.1. Semi-structured interviews

Semi-structured interviews (Creswell, 2014) were conducted with seven stakeholders with an interest in converting plastic waste to filaments for 3D Printing. These interviews were conducted to get deeper insights into their experience, challenges, and aspirations regarding converting plastic waste to filaments for 3D Printing. Therefore, interview questions were structured to collect information on these. The interviews were recorded and transcribed after receiving relevant consent from the participants. These interviews were then thematically analysed, by identifying codes and grouping them into themes which formed the basis for interpretation (Braun and Clarke, 2006). More

Fig. 1. Tech for Trade Extruder.

Fig. 2. Tensile testing of the Tech for Trade filament.

details about these is presented in (Kolade et al., 2022b) This analysis provided insights on both 3D printing and extrusion in low-income settings.

2.3.2. Electronic surveys

Field workers were hired and trained to administer electronic questionnaires to households in 20 low-middle communities across five countries (Kenya, Namibia, Nigeria, Rwanda, Zambia). A total of 1475 households completed the survey (see (Kolade et al., 2022b) for more details). The surveys were administered to measure perception and likelihood of engaging with 3D Printing. Participants responded to the following questions, using a 5-point Likert scale

I How would you rate your understanding of 3D-Printing technology?
II To what extent do you think 3D-Printing technology is useful for recycling plastic?
III To what extent do you think 3D-Printing technology is easy to use?
IV Do you currently use 3D-Printing technology?
V Do you have an intention to use 3D-Printing technology?

3. Literature review

3.1. 3D printing for sustainable development

3D Printing has been recognised as a leading frontier technology that should be utilised within international development by the UK Department for International Development, UNICEF and the United Nations (Ramalingam et al., 2016; UN, 2018). The technology provides a method to leapfrog traditional manufacturing, which is highly capital intensive (Kolade et al., 2022a; Swiss Business Hub and Swiss, 2018) and can also create new businesses and support wealth generation as it was estimated to grow by 23% in 2021 as against 2016 (Shah et al., 2019). Currently, the technology is at a 'tipping point', where it is becoming a feasible manufacturing technique and is considered the cornerstone of the next industrial revolution (Rauch et al., 2016). This game-changing technology is expected to have a substantial impact in low- and middle-income countries (LMICs) as the cost of an entry-level printer has declined from $30,000 to $200 in the last two decades (Berman, 2012; O'Connell and Haines, 2022). In turn, this technology can empower small-medium enterprises (SMEs) by lowering the barriers to manufacturing since there are no tooling costs and one printer can produce specific parts for different applications simultaneously. This has resulted in reduced manufacturing costs and shorter lead times while minimising the reliance on unsustainable and unreliable supply chains. Additionally, 3D Printing allows users to produce complex parts with essentially no waste compared to traditional manufacturing methods. It creates products layer by layer and can control the fill density of the product (Celik, 2020). Therefore, 3D print-based manufacturing can save materials, reduce energy consumption and decrease greenhouse gas emissions, contributing to sustainability (Kreiger and Pearce, 2013; Zhong and Pearce, 2018).

The case for developing 3D printing in sub-Saharan Africa is compelling as globally, there has been a rapid growth of pro-sumer fused filament 3D printers, increase in the availability of open-source designs - some of which can use filaments from recycled plastics, and the growing need for sustainable products by consumers (Cruz Sanchez et al., 2017; Feeley et al., 2014). There are several examples of functional products that have been created from additive manufacturing such as structural heart interventions (Vukicevic et al., 2020), low-cost otoscopes (Capobussi and Moja, 2021), smartphone-based epifluorescence microscope (SeFM) for fresh tissue imaging (Zhu et al., 2020), medical supplies and school shoes for children in Haiti (Ishengoma and Mtaho, 2014), prosthetic limbs (Gretsch et al., 2016) and microscopes for schools in Kenya (Owen, 2018). However, these interventions come with limitations due to the cost and availability of filament replacement for ongoing production (Eboh et al., 2021). This limitation clearly shows the need to develop local capacity and capability to develop filaments with local resources (Arendra et al., 2019).

3.2. A distributed recycling approach – extruding filaments

Due to resource constrains in low income countries, there is a growing call for a distributed approach to recycling. This involves locally managed decentralised networks for collecting, sorting and recycling waste (Joshi and Seay, 2020). This allows consumers to recycle waste in their community thereby eliminating the environmental footprint of transporting waste to centralised collection points. In this approach, plastic wastes would be processed into granules, pellets and/or shredded and sold to up takers or further processed into other products for local use. Lifecycle analysis of the distributed recycling method indicates less embodied energy compared with the best-case scenario for centralised recycling. In fact, Kreiger et al. (2014) notes that more than 100 million MJ of energy was conserved annually, along with substantial reductions in greenhouse gas emissions.

A novel and innovative approach in distributed recycling is local production of filaments for 3D Printing (Garmulewicz et al., 2016; Sanchez et al., 2020). Various scholars such as (Baechler et al., 2013; Cruz Sanchez et al., 2017; Hunt et al., 2015; Kreiger et al., 2014; Woern et al., 2018) have highlighted the feasibility of using this approach of filament production for distributed recycling. Dutch airline, KLM, started using PET bottles to make tools to repair and maintain its aircraft. According to the airline, empty bottles are collected at the end of every flight and transformed into filament, then used in a 3D printer to create new products (KLM, 2019). Converting waste plastics to filaments aligns perfectly with the circular economy model (Kolade et al., 2022a; Pavlo et al., 2018) which aims to keep resources in use for as long as possible and extract their maximum value whilst they are in use (Stahel, 2016; Sverko Grdic et al., 2020). By effectively engaging and communicating with the key stakeholders in the circular economy ecosystem, this intervention will result in a quadruple bottom-line effect by increasing value (profit), reducing waste (planet), encouraging social wellbeing (people) and generating technical innovation (progress) (Gupta et al., 2019) as well as contribute to bridging the circularity divide (Barrie et al., 2022). Producing filaments for 3D printers has shown to reduce the cost of products for example, Heikkinen et al. (2018) showed they could be used for making customised chemical resistant labware that costs 10% less than its market alternative. Furthermore, this approach can be powered by renewable energy which will increase the sustainability metrics and lead to positive environmental impacts (Choudhary et al., 2019; Zhong and Pearce, 2018).

Several scholars have reviewed this concept in the literature; Mikula et al. (2021) presented a comprehensive literature review highlighting the various ways researchers have used waste plastics for 3D printing filament as an alternate approach to the current practice of central gathering of plastics. They highlighted the effect of the conversion process on physicochemical and mechanical properties of the filaments. Similarly, Romani et al. (2021) presented a comprehensive review on waste recycling through extrusion-based additive manufacturing; Shanmugam et al. (2020) reviewed the remanufactured feedstock materials and polymers as well as composites for 3D printing and found significant opportunities for recyclable polymers to be used in 3D printing; while Zander (2019) conducted a review to establish the state of the art of recycled plastics in material extrusion–based polymer additive manufacturing while proffering a view for the future. These reviews indicate the increasing interests from scholars to engage with this concept.

Plastics are converted to filaments through a process known as extrusion. However, several pre-extrusion stages must be undertaken before the filament can be produced. A schematic of the process of converting plastic to 3D products is presented in Fig. 3. First, the plastics are collected and sorted, ensuring that the batch for extrusion is homogenous. The sorting is followed by cleaning, which involves removing labels and the label glue, washing and rinsing. This process ensures that the batch to be extruded contains no contaminants. The cleaned homogenous plastic batch will then be shredded into small flakes in readiness for extrusion. The flakes must be dried as moisture content can affect the extrusion process. The dried flakes can then be fed into the extruder through a hopper (Garmulewicz et al., 2016; Singh et al., 2017; Zander et al., 2018; Zhong and Pearce, 2018). The extruded filament is then cooled and spooled.

Fig. 4 shows a schematic diagram by (Cruz Sanchez et al., 2017) which illustrates the extrusion process. The extrusion process starts with the dried flakes/pellets fed into a hopper through the feeding system, which then drops on a rotating screw controlled by an electric motor. The screw moves the material through a heated barrel which causes the screw channel or thread to decrease, thereby compressing the material. The barrel is then gradually heated by heaters which are controlled by derivative PID controllers that create heat zones. The controllers are usually set to a temperature lower than the melting point of the material being extruded because of the extra heat generated due to the compressive force and shear friction during the process. As the filament melts and approaches the end of the screw, it proceeds through a screen pack, which is anchored by a breaker plate that filters the contaminants and removes the rotational memory. The last step involves the filtered melts passing through a die that provides the required diameter before being pulled through the extruder, cooled and then spooled.

Standards are critical in extruding filaments as diameter consistency is essential to ensure printability and uniformity in the 3D printing process. 3D filaments are typically produced to a tolerance of ±0.05 mm and a corresponding standard deviation and ovality; however, flexibility allows users to select specific spools based on unique requirements. The Ethical Filament Foundation (EFF, 2015) highlighted the need for the advancement of an "ethical product standard" for 3D printing filaments in developing societies. This Ethical filament standards require that the tolerance of 1.75 mm diameter filament should be between 1.6–1.85 mm and 2.85 mm diameter filament between 2.75–3.25 mm (EFF, 2015). The exact diameter limits apply for roundness; hence two measurements of diameter are usually required at each point. They suggest that if filament consistently meets the diameter tolerances advised, it can be used in 3D printers without any problems. The 1.75 mm filaments are more popular and easier to buy. Furthermore, they can be extruded at faster flowrate, use less material, and have faster print speeds. The 2.85 mm filaments are more rigid so they are likely to jam during printing and easier to print when using flexible plastics.

Fig. 3. The Basic steps of converting waste to 3D printed products.

3.3. Extruder development

Several scholars have investigated the feasibility of producing 3D printing filaments from end-of-life plastics leading to individuals, researchers, and start-ups developing extruders. A notable example is the RepRapable Recyclebot, developed by researchers at the Michigan Technological University (Woern et al., 2018). They developed an open-source plastic waste extruder that used both virgin and recycled plastics to produce filaments. According to the study, the RepRapable recyclebot, costing approximately $700, can produce filament from a wide range of thermopolymers as it can handle polymers with melting point temperature of up to 250 °C. They produced filaments with diameter tolerance of ±4.6% at a rate of 0.4 kg/h using 0.24 kWh/kg of energy. However, the study focused mainly on the development of the extruder and only reported on the results obtained when using PLA plastic. Although the produced filament was effectively used to produce 3-D printed parts, the study did not report the quality of the filament (e.g., crystallinity, viscosity, mechanical properties and degradation temperature). An additional limitation of the study is that only one parameter (temperature) for the extrusion process was explored during testing. However, other studies (Haq et al., 2017; Mirón et al., 2017) have shown that the extrusion speed, the cooling rate and the spooling mechanism all affect the filament quality. The RepRapable recyclebot was an open-source project, and many other variants have been developed with varying levels of success. For instance, the RepRap developed by Baechler et al. (2013) recycled HDPE to produce filament, which was successfully used in a 3-D printer. However, their results showed significant inconsistencies in the filament diameter, which is a shortcoming as it could cause the 3-D printer to get clogged up and malfunction. Hachimi et al. (2021) designed and tested a locally built extruder which could use thermoplastics from pellets, granules and plastic waste. The device was used to extrude PA6 polymer and the resulting filaments was found to have significantly lower performance. Mohammed et al. (2018) developed a device for recycling ABS plastics from E-Waste into filaments for 3D printing. This process was termed Ecoprinting due to the use of renewable energy. Their study demonstrated that this approach could be a cost-effective relief solution for vulnerable societies in developing environments. Petsiuk et al. (2022) presented a proof of concept which is a unique open-source hybrid printer that is low cost and designed to allow the extrusion of large volumes of recycled plastic waste.

There are several examples of extruders developed outside of research organisations. The Lyman Filament Extruder (Lyman, 2015; McCracken, 2013) and the MiniRecycleBot (RepRap, 2012), are examples of extruders developed by individuals. The Lyman extruder can produce filament from ABS and PLA pellets while the MiniRecycleBot can produce filament from HDPE and LDPE. Similarly there are now several filament extruders which are available commercially, although these are usually too expensive for the sub-Saharan African context.

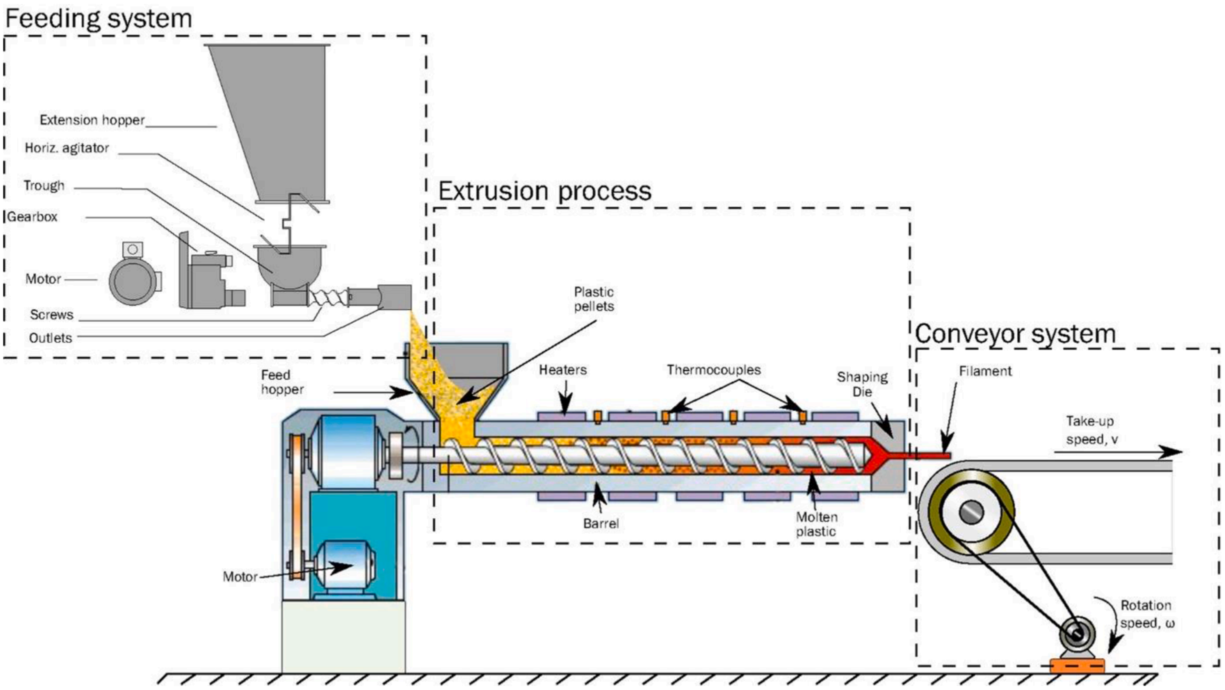

Fig. 4. Schematic diagram of the extrusion process for the fabrication of 3D printing feedstock, Source (Cruz Sanchez et al., 2017).

Some of the common commercially available filament extruders are presented in Table 1. These include the Filabot (Filabot, 2020), Felfil Evo (Felfil, 2020), the Composer (3Devo, 2021) and the Filastruder (Filastruder, 2020). However, most of these extruders have not been subjected to independent, rigorous evaluation to substantiate the manufacturers' claims. One of the few reports on commercially available extruders was done by Ghabezi et al. (2022) who used commercially available filament extruder Noztek Touch Dual PID filament maker, to produce filaments from recycled mushroom trays made of Polypropylene (PP). The filaments were strengthened by integrating recycled basalt fibres during the extrusion. Also, 3-D printing filaments made from recycled plastics are commercially available. Companies such as Filamentive, use post-consumer and post-industrial waste to produce a wide variety of 3-D printing filament; these include PLA, ABS, ONE PET. Nevertheless, scientific publications evaluating the filament quality are scarce. Therefore, this study contributes to the literature by providing details on the suitability of commercially available extruders and filaments for sub-saharan Africa.

3.4. *Characteristics of extruded filaments*

Several scholars have highlighted reduced quality of filaments made from waste plastic. This is not surprising as one will expect material properties to degrade with each recycle run. Gaikwad et al. (2018) explored upcycling of electronic waste (e-waste) plastics derived from end-of-life printers, mainly polycarbonate, into 3D printing filaments. They found that the extruded filaments could produce up to 83% tensile strength of a virgin counterpart while achieving 28% reduction in carbon emissions. Lanzotti et al. (2019) compared the mechanical properties of 3D printed parts made using virgin and recycled PLA. They found the short beam strengths to be 119.1 MPa (Virgin), 106.8 MPa (One time Recycled), 108.5 MPa (Twice Recycled) and 75 MPa (three times recycled) which showed recycling as a viable option since the recycling filaments could result in up to 90% of the virgin filaments. Hart et al.

Table 1
Filament Extruders.

Company	Extruder	Cost (£)	Production Rate	Stated Tolerances (mm)	PET compatible; Maximum temperature
ReDeTec	ProtoCycler	2633.45	500 g/hr	±0.05	Yes; 250 °C
Felfil	Felfil Evo	612.08	1.15 m/min	±0.07	N/A;250 °C or 300 °C
3devo	3devo Composer 350/450 and Precision 350/450	5068.64/5920.51 and 4514.41/5366.50	0.7 kg/hour	±0.05	Yes; 450 °C
Filabot	Filabot EX2 and EX6	2115.25 and 7928.50	0.91 kg/hr (EX2) 4.5 kg/hr (EX6)	±0.05	Yes; 400 °C (EX2) 350 °C (EX6)
Filastruder	Filastruder Kit	225.56	5–8 kg/hr	±0.05	N/A;260 °C
Noztek	Noztek Pro	1195	1 kg /2 hrs	±0.04	N/A;300 °C
N/A	RepRapable Recyclebot	<526.50	0.4 kg/hr	N/A	Yes; 250 °C
N/A	Lyman Extruder V6/V7	~301.06	1/2 lb/hr5 min/min	±0.06	YES; 285 °C
TechforTrade	Thunderhead Extruder	Depends on local prices	0.75 kg/hr	±0.25 (approximate)	Yes; 175 °C
Omnidynamics	Strooder	>242.50	0.7 m – 1.5 m/min	±0.1	YES; 250 °C
WellZoom	Wellzoom B2 Desktop	513.71	300 mm/min ~ 650 mm/min	±0.05	YES; 300 °C
Precious plastics	Extrusion Pro	1510	NA	NA	No; NA
Akabot	Akabot 2.0	377.73 – 566.59	NA	NA	Yes; 250 °C

(2018) investigated the potential of converting Meals Ready to Eat (MRE) pouches to filaments and observed that the properties of the resulting 3D printed products were comparable to native pouch materials. On the other hand, Sasse et al. (2022) investigated the mechanical performance of coextruded (core layer with high recycled PLA content and a skin layer from virgin PLA) filaments and observed them to have inferior mechanical properties compared to the monoextruded counterparts but suggested that this approach could save on the feedstock as it could be used for the outer layer.

The literature suggests that the extrusion speed, extrusion temperature, the cooling rate and the spooling mechanism can affect the filament quality. Devra et al. (2022) investigated the effect of temperature while converting LDPE waste (which usually have no commercial interest) into filaments. Extrusion was done at 150 °C, 180 °C and 210 °C and they observed that extruding at higher temperature resulted in better mechanical properties and surface texture while the chemical bonding is unaffected by the extrusion temperature. Herianto et al. (2020) conducted a study to optimise the extrusion process for Recycled Polypropylene Filament for 3D Printers and recommended a spooler speed of 4 rpm, extrusion speed of 40 rpm, and extrusion temperature of 200 °C. Raza and Singh (2020) studied the process of converting discarded plastics into filaments and found that the speed and temperature of extrusion have a substantial effect on filament thickness. Nassar et al. (2019) designed and constructed a filament extruder and further tested it using virgin HDPE. They suggested that in order to get high-quality filament, the temperature and extrusion rate need to be appropriately set, recommending a motor speed of 18 rpm and a temperature in excess of 200 °C for HDPE. Geng et al. (2019) studied the effects extrusion speed and printing speed using polyether-ether-ketone (PEEK) and suggested that improving the stability, dimensional accuracy and surface morphology of printed by optimising the extrusion speed and the diameter of the extruded filament through a control algorithm. Cardona et al. (2016) who extruded ABS reported achieving high diameter consistency and low tolerances (0.01 mm) at low extrusion temperature (180 °C) and low extrusion rate (10 in/min). To cater for the common problem of inconsistent filament diameter, Petsiuk and Pearce (2021) designed, constructed, tested and validated an open-source filament diameter sensor that could be used as a control mechanism for extruders. The tests, which were conducted using ABS and PLA as well as using various colours including clear plastic, yielded promising results.

A very important consideration for the extrusion process is health and safety. Stefaniak et al. (2022) used standard industrial hygiene methodologies to study the emissions released during extrusion, of recycled PLA and ABS as well as virgin ABS, PLA, ABS, HDPE, LDPE, PS and PP pellets. They found all samples released particles containing hazardous metals such as manganese, with particle size in the range that could be deposited in the gas exchange region of the lungs. They observed that the vapors released during the process was found to contain respiratory irritants and potential carcinogens (benzene and formaldehyde), mucus membrane irritants (acetone, xylenes, ethylbenzene, and methyl methacrylate), and asthmagens (styrene, multiple carbonyl compounds).

3.5. *The case for PET*

PET is one of the easiest plastics to identify, with little education and training required. They also have several desirable properties such as higher bulk strength, stiffness and elastic modulus (Zander et al., 2018). In addition, they are lightweight and easy to transport, have good gas and moisture barrier properties and provide resistance to alcohols, aliphatic hydrocarbons, oils, greases and diluted acids, and good thermal stability (Awaja and Pavel, 2005). These properties make PET an attractive feedstock for filament production and 3D Printing. Furthermore, since PET is widely used for diverse applications across various sectors, it makes up a substantial proportion of the plastic waste stream in sub-Saharan Africa (Adefila et al., 2020; Zulkifley et al., 2014). However, studies have shown that printed parts have substantially reduced strength due to voids and weak interlayer adhesion (Zander et al., 2018).

Even though several studies have examined the use of recycled materials for filament production, most of these studies used high-density polyethylene (HDPE), acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), with very few successful studies on PET reported. This, coupled with the fact that it is not biodegradable, makes reusing or recycling a practical way to reduce PET waste (Zander et al., 2018). Moreover, in 2030, the global demand for PET is forecasted to amount to 42 t (Dybka-Stępień et al., 2021). Therefore, the mainstreaming of the concept of filaments from waste plastics in sub-Saharan Africa will receive a huge boost if PET can be successfully converted to filaments in a low income setting.

There are two main ways of recycling plastics, mechanical and chemical recycling. As mentioned above, to produce filament from plastic waste, the plastics must first be cleaned, dried, and then grinded into small flakes; this process is what is referred to as mechanical recycling. According to Garmulewicz et al. (2016) mechanical recycling of PET results in an amorphous product with a higher percentage of crystallinity, which can lead to a more brittle extrudate, or can cause the material to crystalise in the nozzle of the 3-D printer, and therefore cause clogging. To combat this, chemical recycling is employed to depolymerise and purify the recycled PET before it is reused to fabricate filaments (Garmulewicz et al., 2016). This process can be achieved by using ethylene glycol to modify the recycled PET resulting in a new product called polyethene terephthalate glycol, PET-G. Alternatively, virgin PET flakes can be mixed with recycled PET flakes to obtain a higher-quality extrudate (Zander et al., 2018).

Zander et al. (2018) noted that PET is a suitable material for filament production, provided it is properly cleaned and dried, as contamination and moisture are the main factors that lead to the deterioration of materials' physical and chemical properties during the extrusion process. Additionally, they highlighted that in order to produce uniform filament diameter from recycled PET, multiple extrusion cycles should be performed (Zander et al., 2018). Garmulewicz et al. (2016) observed that neglecting the connection between an appropriate extruder setup (optimal temperature, extrusion speed, cooling rate and spooling mechanism) and filament quality, would result in poor quality filaments. In their study, Zander et al. (2018) describe optimal extruder setup for the production of PET filament. Although they provide a strong base for investigating the appropriate extruder parameters for PET, their research fails to address the operating environment's impact (e.g., ambient temperature) has on the obtained results.

The Akabot was developed by the Santa Clara University, which was to be deployed in Uganda, for producing low-cost 3-D printing filament to manufacture solar lanterns. The results showed that filaments produced solely from PET bottles were very brittle due to increased crystallinity (Dubashi et al., 2015). To mitigate this issue, virgin PET pellets were mixed with the recycled PET bottles, which resulted in a much better filament. However, the produced extrudate was not usable in a 3D printer (Dubashi et al., 2015). The Akabot project also recorded difficulties with temperature control. The researchers noted that the machine could not produce filament during testing due to very high temperatures, which resulted in burnt plastic in one of the tests. In addition, heat loss caused the plastic to solidify before reaching the filament nozzle on another occasion (Dubashi et al., 2015) . This was likely due to the lack of insulation used on the heating barrel. Moreover, the Akabot also lacked a cooling mechanism and a spooler for the filament.

The Thunderhead is another example of an extruder that uses PET waste to produce filament. It was developed in Kenya by Tech for Trade, specifically for low-income settings; thus, the machine can be built from affordable and readily available materials (Rogge et al., 2017). The Thunderhead extruder utilises a water bath to cool the filament and has automatic spooling. Unfortunately, results obtained from the

Thunderhead extruder show that it cannot produce a filament with a consistent diameter (Rogge et al., 2017). This is likely due to inconsistencies between the extrusion speed and the spooling mechanism. These identified challenges illustrate the need for more research and development on the subject. Table 1 presents some of the extruders available, highlighting which claim to be suitable for PET extrusion.

The literature review has highlighted that despite the progress in 3D printing and extrusion, there is still a wide gap in knowledge on how this process could be operationalised and deployed at scale especially in sub-Saharan Africa. Furthermore, there is still significant scope for developing extruders for PET. A testament to this is the low adoption of this concept even though it has been tipped as a viable recycling solution. Therefore, this paper aims to fill this gap by providing novel insights on converting waste plastics to 3D printed products in Sub-Sahara Africa.

4. Results and discussion

4.1. *Experimental*

4.1.1. *Extruders*

As stated previously, three off the shelf extruders were purchased for testing but extensive experimentation was only possible with one - Noztek Pro. The results showed that an increase in temperature resulted in a decrease in filament diameter (and vice versa). It was observed that once a good extrusion temperature was achieved, only small adjustments needed to be made, within ±8 °C of the average. Furthermore, the average rate of extrusion recorded during these experiments indicates that 1 kg roll of 2.85 mm diameter filament (either PLA or XT) could be produced per day.

Table 2 summarises the results obtained using the different materials from several tests to produce high quality 2.85 mm filament, while Fig. 5 shows the fluctuation in diameter during the extrusion process. These show that the filament diameter fluctuated significantly, indicating that the filaments would be unusable. The 3D printer gear is likely to be clogged up with oversized filament or not grip the filament when undersized. It was observed that maintaining a constant feed of materials from the hopper to the screw resulted in a higher quality filament. This was typically seen with the latter two PLA experiments, but tests with XT showed inconsistent material feed and that the temperature profile was harder to stabilise. Even though most of the results do not consistently meet the standards for high-quality filament, 60% of the filament can meet Ethical Filament's standards.

As stated earlier, there is an inverse relationship between temperature and diameter, i.e., a higher extrusion temperature leads to the thinner filament and vice versa. In any case, it is advisable to discard the first 2 m of the filament extruded, as this was repeatedly found to be inconsistent, and temperature changes made beyond this point do not noticeably affect the filament diameter. Similarly, it was observed that the cooling rate needs to be optimal as cooling too slow will result in the filament sagging and/or sticking together on the spool. Cooling too fast will decrease crystallinity, effectively freezing the polymer microstructure in place before the polymer chains can become completely organised. Therefore, the setup will benefit from a control system based on a real-time feedback loop that optimises the design and operation parameters such as temperatures, filament diameter, extrusion speeds etc. This requires developing a mathematical model that includes all the design and operating parameters (Azadani et al., 2022). Tests with PET flakes did not show promising results on the Noztek pro. It is also worth noting that the two other brands of extruders produced highly inconsistent diameter filaments that were unusable. A pertinent observation in all three extruders tested was the issue of health and safety during operation. As Stefaniak et al. (2022) observed, the emissions from the extrusion process can be quite harmful (Ágnes and Rajmund, 2016; Ţiplica et al., 2020). Therefore, sufficient ventilation must be in place to ensure safety of the operator.

4.1.2. *Filaments*

Table 3 shows results from tests conducted on commercially available filaments. The results show that the PLA and PET filaments meet the standards set for high quality 2.85 mm filament. Refil and Filamentive's 1.75 mm filament meet the standards for high quality on >79% of occasions, Zortrax's 1.75 mm filament does not consistently meet the high-quality filament standard. This discrepancy between the filament diameter standards and the measured diameter can be explained by the fact that Zortrax's filament is designed to work only on their printers. The results show that the filaments from Tech for Trade's Thunderhead extruder is mostly inconsistent, however, they have modified their 3D printers to accept filament that are outside of the conventional range (Rogge et al., 2017).

Table 4 shows the results of the tensile test on two samples. It can be

Table 2
Results from extrusion with Noztek Pro.

Test Number	Material	Average (mm)	+ Tolerance (mm) {Value}	- Tolerance (mm) {Value}	Standard Deviation (mm)	High Quality Percentage	Ethical Filament Quality Percentage
1	PLA	2.80	0.30 {3.10}	0.33 {2.47}	0.132	48.84	68.49
2		2.79	0.40 {3.19}	0.31 {2.48}	0.113	61.05	69.47
3		2.72	0.24 {2.96}	0.26 {2.46}	0.136	47.16	48.30
4		2.77	0.44 {3.21}	0.38 {2.39}	0.137	38.16	68.42
5		2.75	0.56 {3.31}	0.42 {2.33}	0.109	53.06	66.94
6		2.75	0.19	0.24	0.078	51.34	71.91
7		2.79	0.25	0.40	0.113	60.18	75.11
8	XT	3.15	0.56 {3.71}	0.99 {2.16}	0.293	12.17	53.91
9		3.01	0.48 {3.49}	0.46 {2.55}	0.225	17.46	68.25
10		2.97	0.86 {3.83}	0.80 {2.17}	0.273	34.76	73.26
11		2.95	0.68 {3.68}	0.62 {2.33}	0.235	31.90	68.53
12		2.90	0.67 {3.57}	0.60 {2.30}	0.251	28.95	61.99
13		2.98	0.46 {3.44}	0.58 {2.40}	0.186	34.00	78.67

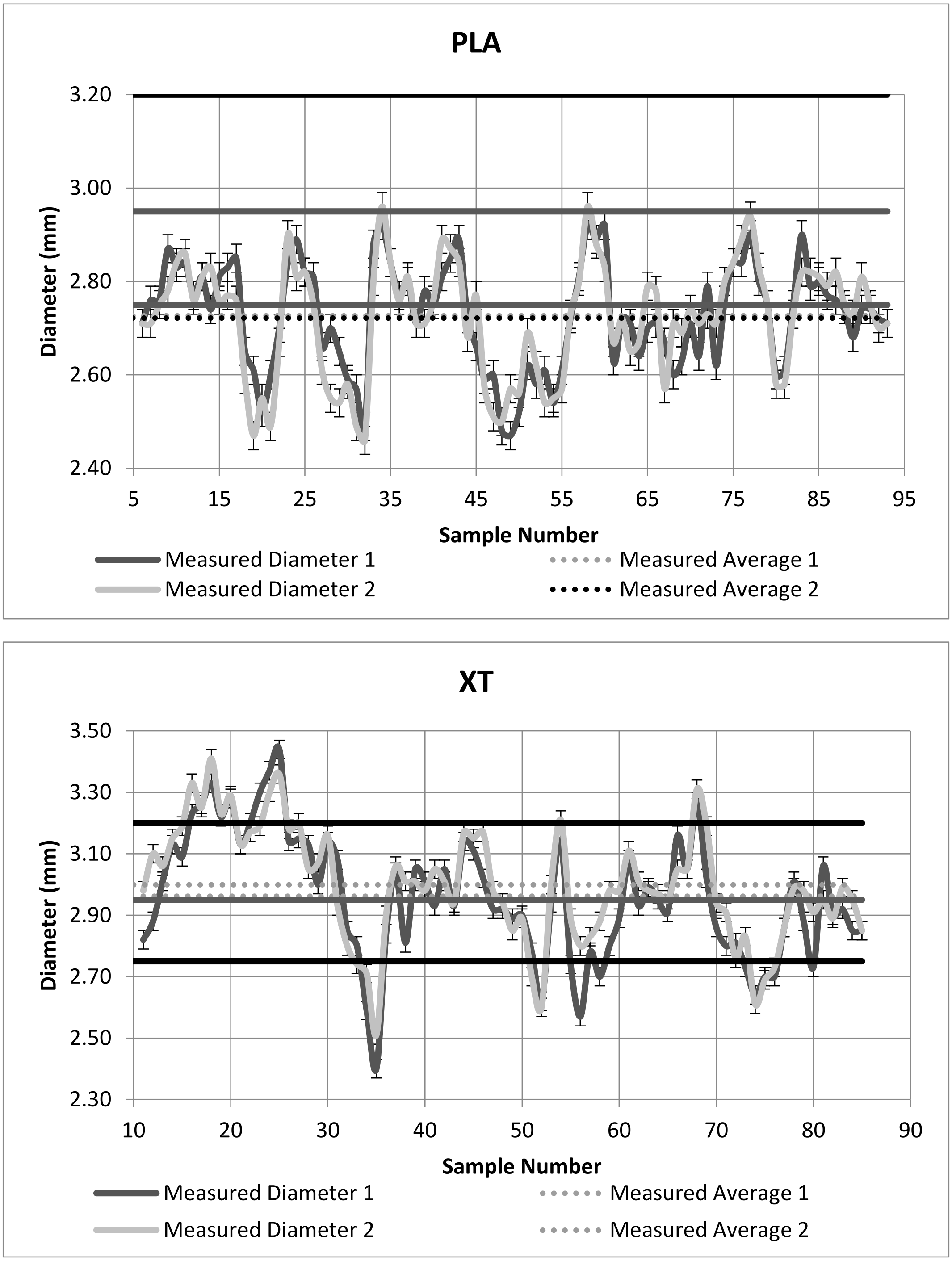

Fig. 5. Fluctuation in filament diameter during extrusion in (a) PLA (b) XT.

observed that the two samples have varying results despite being similar. This can be attributed to the poor filament quality which means that the strength of the filament will be inconsistent and unpredictable. Secondly, it can be observed that the ductility in both samples is less than 7% which is much lower than expected from virgin plastics.

4.2. Stakeholder engagement

As highlighted, a cross sectional engagement with stakeholders in sub-Saharan Africa was conducted to characterise the socio-cultural factors affecting the uptake of the process. Firstly, electronic surveys were used to gain insights about the perception of 3D Printing technology in low-income communities. Fig. 6 presents the results, using five categories (1) Understanding of technology (2) Usefulness of technology for managing plastic waste (3) Opinion on ease of use of technology (4) Previous experience using technology (5) Openness to use technology. The findings indicate that less than 15% of respondents have previously used or understand the technology, suggesting the need to build local capacity. Building local capacity will create opportunities for the growth of the SME sector to develop the technical skills required to manufacture products locally (Rogge et al., 2017). The need to build capacity for operating, developing and maintaining 3D printers and extruders locally was also highlighted by interview participants. Furthermore, 3D printers and extruders for sub-Saharan Africa must be

Table 3
Results from filament tests.

Filament	Average Diameter (mm)	+ Tolerance {Value} (mm)	- Tolerance {Value} (mm)	Standard Deviation (mm)	High Quality Percentage	Ethical Filament Quality Percentage
Zortrax ULTRAT Spool 1	1.63	0.20 {1.83}	0.10 {1.53}	0.042	21.72	78.28
Zortrax ULTRAT Spool 2	1.65	0.17 {1.82}	0.26 {1.26}	0.044	47.90	84.45
Filamentive ONE PET	1.71	0.07 {1.78}	0.08 {1.63}	0.037	92.42	100.00
Refil Blue PET	1.70	0.12 {1.82}	0.12 {1.58}	0.045	79.55	99.24
TechforTrade PET Spool 1	1.68	0.41 {2.09}	0.55 {1.13}	0.201	23.85	43.85
TechforTrade PET Spool 2	1.56	1.00 {2.56}	0.43 {1.13}	0.169	15.38	30.00
Refil Blue PET	2.85	0.06 {2.91}	0.05 {2.81}	0.023	100.00	100
Refil Transparent PET	2.86	0.06 {2.92}	0.06 {2.79}	0.021	100.00	100
Refil Mixed PET	2.80	0.07 {2.88}	0.10 {2.71}	0.032	97.50	100
Ultimaker White PLA	2.86	0.04 {2.90}	0.06 {2.80}	0.021	100.00	100
Ultimaker Silver Metallic PLA	2.87	0.06 {2.93}	0.04 {2.83}	0.027	100.00	100

Table 4
Tensile test results for Thunderhead filament.

Testing specimen	*Maximum applied load in testing (N)*	*Tensile Strength* ($\boldsymbol{MNm}^2$)	Extension at break (mm)	Original gauge length (mm)	Over-all Extension After break (mm)	Ductility in Percentage (%)
Sample 1	*446*	*18.5*	0.762	33	33.762	2.30
Sample 2	*877*	*36.54*	2.178	33	35.178	6.6

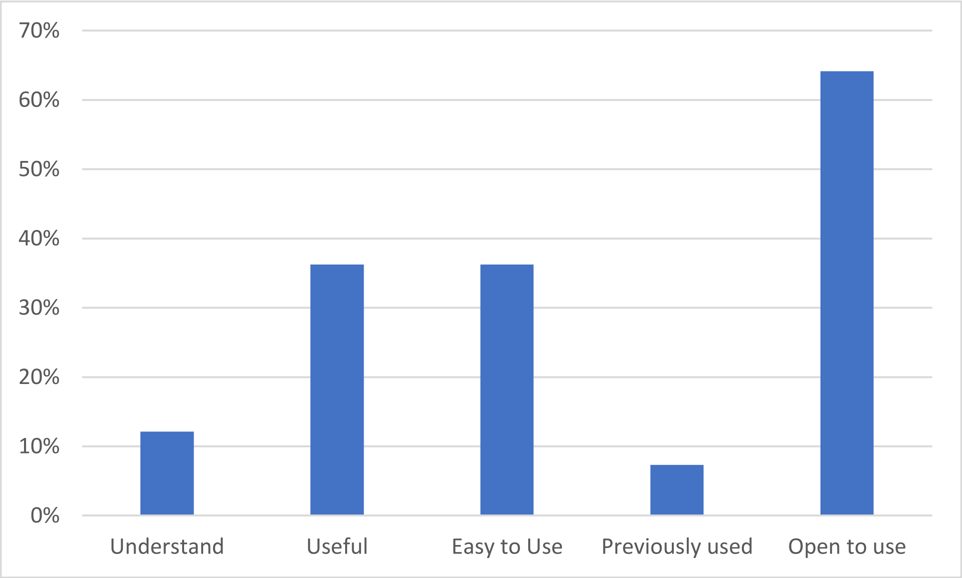

Fig. 6. Perception of 3D Printing.

robust, reliable and durable to prevent the need for constant repairs (Minetola and Galati, 2018). This is pertinent because, firstly, a significant proportion of the population in low-income communities of sub-Saharan Africa are not highly skilled so there may be shortage of labour to meet a constant demand. Secondly, the complexity of the supply chain in Africa implies that there may be significant delays in receiving replacement components. A simplified design using local materials and upcycled components will go a long way in aiding this, as personnel will be familiar with the materials.

The recent COVID-19 outbreak highlights the need for collaboration and cooperation between nations, especially around technology transfer, particularly with organisations with a high level of production and innovative capacity (Santiago et al., 2020). This, therefore, requires high-income countries to collaborate with middle- and low-income countries to build the capacity for technology transfer in 3D Printing. The survey further shows that over 60% of respondents are open to using it, suggesting that it is likely to have significant uptake locally, if the technology is well developed and suited for the local context. This observation was supported with data from the interviews for example, one respondent noted "3D printing is a technology that I am sure many would like to embrace but are unaware of where or how to start"

Despite the merits of 3D printing in low-income settings, there are barriers limiting its success in sub-Saharan Africa. For example, one of the themes that emerged from the interviews was the lack of access to basic infrastructure - electricity, water, and transportation systems. This has significant implications for the adoption and smooth operation of the technology. For example, the 3D printer, and other processes such as extruder and model designing, require electricity to run, therefore, an erratic power supply will impede the development of this technology. The viability of both 3D Printing and extruder technology in sub-Saharan Africa will depend heavily on the economics. Firstly, the issue of affordability needs to be considered; even though entry-level 3D printers could cost less than $200, this is still very expensive for people in low-income communities (Aghimien et al., 2021; Zahid et al., 2019). Secondly, the affordability challenge is exacerbated by the fact that access to finance is usually a challenge in Sub-Saharan Africa (Abraham and Schmukler, 2017; Wang, 2016). A potential way to bring costs down will be to manufacture 3D printers and extruders locally (Ngo et al., 2018), using local materials and upcycling existing components from electronic waste. Giving the financial challenges, it is pertinent to conduct financial forecast such as estimating the return on investment and payback period for a community setup.

Some of the results from the stakeholder engagement were in tandem with what was observed during the experiments as well as agreed with published work. Some interview participants noted how they have struggled to simultaneously optimise speed, cooling rate and spooling mechanism. This illustrates the need for mathematical models'/control mechanism which can optimise the extrusion process based on ambient conditions and input parameters. For example, the cooling rate in a lab in London will be significantly different from that in Nairobi due to the temperature differences; therefore, parameters need to be adjusted to meet the required cooling rate. Data from interviews in Kenya also highlighted that temperature variations from day to night typically disrupted the extrusion process. This highlighted the need to have a controlled environment maintained at a constant temperature.

The results from the interviews showed that the resulting filaments from the extrusion process often came out brittle which was also observed by Yamamoto et al. (2019). In addition, the mechanical properties of the plastics degrade with each recycling run. A potential intervention to tackle this challenge, will be the development of low-cost additives which can increase the filament strength (Sanchez et al., 2015). For example, Pringle et al. (2018) found that waste generated from furniture could be used to improve filament quality with the addition of biopolymer polylactic acid and other additives. The inconsistency in filament diameter is another theme identified by interview participants which could be addressed by fitting a diameter sensor to the extruder such as the one developed by Petsiuk and Pearce (2021).

The engagement with stakeholders showed that the development of 3D printing technology can contribute significantly to social life as also noted by Lupton (2016). This is because it enables endless transformational possibilities, including the creation of new, innovative, locally made unique products which meet specific local needs (Savonen, 2019; Wu et al., 2022). For example, bespoke products used in cultural events such as local theatres and festivals could be produced from 3D printing since other manufacturing methods might be impractical and/or not economically attractive. Adopting a local production approach also mitigates the difficulty in getting consistent supplies of affordable filament for 3D Printing across sub-Saharan Africa. However, to accelerate progress, governments across sub-Saharan Africa need to play a critical role (Scott et al., 2012) in areas such as creating clear standards and policies, investing in capacity and skills to develop, deploy and maintain the technologies, as well as providing financial incentives to encourage participation.

5. Conclusion

The development of the 3D printer technology can transform low-income societies with underdeveloped infrastructure and inadequate manufacturing capabilities while ensuring scalability that is free and agile based on the use of open-source designs. However, a significant barrier to the uptake of 3D Printing in Sub-Saharan Africa is the costs of filaments. A promising solution to the high costs is the local production of filaments using plastic waste, which is readily available and has outstanding properties. This approach reduces the costs and helps tackle the environmental menace of plastic pollution.

This study used a transdisciplinary approach to examine the potential of converting plastic waste to 3D printed products in Sub-Saharan Africa. A critical review of the literature indicated that while several extruders have been developed in the last decade, there are still many challenges some of which include difficulty to produce filaments with consistent diameter, degraded mechanical properties and health hazards from emissions during extrusion. Only one of the three extruders purchased was able to produce reasonable lengths of filaments. It was further observed that operating parameters such as temperature had a significant impact on the quality of the filament. The stakeholder engagement showed communities had significant interest in adopting the technology but do not have sufficient understanding. The findings revealed building local capacity to develop, operate and maintain technologies associated with 3D printing as critical for the success.

The following recommendations are made for the successful deployment of 3D printing at scale across sub Sahara Africa

- Extrusion devices need to have better integrated control for optimising extrusion using real-time inputs such as ambient temperature, extrusion temperature, extrusion speed, cooling rate and spooling mechanism.
- 3D printers which are more tolerant of the inconsistency in filament diameter will be a more practical option for the continent.
- Given the high cost of commercially available extruders, their performance and suitability need to be tested on a case by case basis.
- Chemical additives or virgin plastic need to be added to the feedstock to tackle the challenge of brittle filaments, especially when using PET. Therefore, local low-cost materials that can be used as additives need to be identified and/or developed
- From a practical perspective, it is important to plan around the lack of basic infrastructure such as access to electricity, water and transportation systems. For example, providing off-grid standalone alternate power supply from solar energy.
- It is important to build capacity and capability of local skills to operate, maintain and develop 3D Printing and extruder technology.
- The process of converting waste plastics to 3D printed products results in toxic emissions, consequently, adequate ventilation and protection need to be in place while undertaking extrusion.

The long-term sustainability and success of 3D printers in low- and middle-income economies at a required scale depend on various variables. It also depends on the ability to overcome some of the identified challenges related to ensuring the quality of the filaments produced as well as having the capacity and capability to maintain 3D printers and extruders locally.

CRediT authorship contribution statement

Muyiwa Oyinlola: Conceptualization, Funding acquisition, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Silifat Abimbola Okoya:** Writing – original draft, Writing – review & editing. **Timothy Whitehead:** Funding acquisition, Methodology, Investigation, Writing – review & editing. **Mark Evans:** Funding

acquisition, Investigation. **Anne Sera Lowe:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Muyiwa Oyinlola reports financial support was provided by Engineering and Physical Sciences Research Council. Timothy Whitehead reports financial support was provided by Engineering and Physical Sciences Research Council. Muyiwa Oyinlola reports financial support was provided by Royal Academy of Engineering.

Data availability

Data will be made available on request.

Acknowledgement

The project is supported by the UKRI GCRF under Grants EP/T0238721 and EP/T029846/1 and the Royal Academy of Engineering through the Frontiers of Engineering for Development (FoESFt5\100014).

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