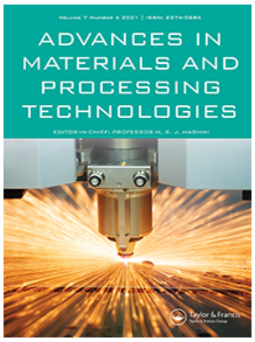

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Advances in 3D printing materials processing-environmental impacts and alleviation measures

J. Nyika[a], F.M. Mwema[b,c], R.M. Mahamood[b,d], E.T. Akinlabi[a,e] and TC Jen[b]

[a]Department of Geoscience and the Environment, Technical University of Kenya, Nairobi, Kenya; [b]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa; [c]Department of Mechanical Engineering, Dedan Kimathi University of Technology, Nyeri, Kenya; [d]Department of Materials and Metallurgical Engineering, University of Ilorin, Ilorin, Nigeria; [e]Pan African University Institute of Earth and Life Sciences (PAULESI), University of Ibadan, Nigeria

ABSTRACT

Additive manufacturing is one of the most promising contemporary technologies with the ability to revolutionise, fasten, customise and decentralise manufacturing. This short review explores the technology in reference to its environmental impacts and suggests solutions to reduce negative impacts. 3D printing was claimed to reduce energy consumptions and carbon dioxide emissions compared to conventional machining technologies. These advantages, however, depend on the printing technology and material used. 3D printing has been suggested to be energy inefficient, produce waste from support beds and low-quality prints and emit particulate matter and toxic volatile organic compounds, which are harmful to the environment and human health. Metals were found to be the most recyclable and most suitable for an optimised circular economy adopting additive manufacturing. To reduce these impacts, it is prudent to minimise active print time per product, reduce the idling time of printers, use greener, biodegradable or recyclable printing materials and optimise the printing orientation and geometrics to prevent material wastage.

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Additive manufacturing; 3D printing; environment; pollution; manufacturing

1. Introduction

Additive manufacturing, which is commonly referred to as 3D printing is a technology that enables the creation of three-dimensional solid objects by laying down sequential layers of a specified material [1]. 3D printers used in this technology have been used previously in industrial processes to enable prototyping. However, emergent applications include production of intricate and customised geometrics as well as manufacture of modified parts often used in the manufacturing lifespan [2]. According to 3, the latest advances in metal additive manufacturing have enabled the production of hard to manufacture components of complex structural orientations that are impossible to fabricate using conventional manufacturing approaches.

Unlike the conventional manufacturing approaches that are subtractive and involve refining bulk products to make finished ones, additive manufacturing begins with lighter

CONTACT F.M. Mwema fredrick.mwema@dkut.ac.ke Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa

Table 1. A comparison of 3D printing technology to traditional manufacturing processes [27].

Qualities of 3D Printing Technologies compared to Traditional Manufacturing	Impacts on Resultant Products	Impacts on Production Processes
On-demand production	Low	Very High
Production at or near the market or place of use	Medium	Very High
Reduction in weight of products made	Medium	Low
Reduced production of waste	Medium	Medium
Timely reach of products to target market		
Reduction and simplification of complex parts and sub-parts		
Flexible and easy designing and modifications of designs	High	Medium
Customised productions based on the demands of users	Very high	High
Production of novel products that overlook traditional designing and manufacturing conditions		
Production of intricate designs and products that were previously impossible to manufacture		

components and works by addition to refine a final product. Table 1 describes some advantages of additive manufacturing that positions it better than conventional manufacturing practices in aspects of resultant products and processing. The designs used in the technology can be shared with domestic users by uploading and downloading them for wide applications at local levels. A variety of materials and processes enable 3D printing. The printers used also vary widely based on size, which ranges from briefcase sized to those that can print an entire house [4]. The quality and definition of the final products of the process also varies. The different technologies, processes and materials used in 3D printing are detailed in Table 2.

Applications of 3D printing technology are evident in a wide range of industries including the automotive, aerospace, packaging, jewellery making and toy manufacturing, just to name a few [5]. Applications span from rapid prototyping, which optimises designs prior to the production of final products, to the creation of moulds and mould templates useful in massive production [6]. Figure 1 summarises the various applications of 3D printing technology. Although the application of the technology is expanding to include large-scale production of spare parts, for instance, print time is a limiting factor to volume applications.

3D technology is the next frontier in the industrial revolution owing to its ability to decentralise manufacturing and make it localised and mass-customised. According to 9, the technology is widespread worldwide, flexible and a powerful tool to advance manufacturing and production industries. Similarly, 5,hailed the technology in advancing distributed manufacturing, correcting internal production inefficiencies and being the most sought-after technology in contemporary marketing and design sectors. Although the advantages of the technology associated with on-demand production and mass customisation are reported, the reality is that the technology also has some cons that hinder its strong impact in additive manufacturing as supposed. These challenges span from job losses owing to overreliance on automation, copyright and ethics issues resulting from counterfeiting, limited variety of printing materials and uncontrolled manufacture of weapons [9]. Obstacles associated with size restrictions, cost and time inefficiency of the technology compared to traditional manufacturing approaches have been raised [1]. This mini-review focuses on the environmental impacts of 3D printing technology with the aim of alleviating the negative impacts. The keywords used to search for the literature in this mini-review include 3D printing technology, additive

Table 2. Technologies, processes and materials used in 3D printing [9].

Type of Technology		Processes Involved	Material
Extrusion based	Fused Filament Fabrication (FFF) Fused Deposition Modelling (FDM)	The filament is heated to melting and forced out as thin strips through a hot nozzle. Using many extruder heads, objects of different materials and colours can be printed.	-Thermoplastics such as polylactide (PLA) and acrylonitrile butadiene styrene (ABS) -Wooden and metal-wire like composite filaments
Granular material binding	Power bed printing	Using inkjet print to bind cross-sections and an inkjet printer to apply resin on plaster between layers, the approach prints elastomer parts and full-coloured prototypes.	-Ceramic powders -Metal alloys -Elastomers -Polystyrene (PS) -Polyamide (PA) -Polyether ether ketone (PEEK)
	Electron beam melting (EBM)	A high-vacuumed electron beam is used to melt metal layers sequentially	
	Direct metal laser sintering (DMLS) Selective laser sintering (SLS)	Lasers are used to sinter (fuse) powder layers to build an object. Non-fused media is used as support for the product being printed.	
Light	Polymerised	UV inkjet printing	Ultra-thin layers cured using UV light are applied photopolymers using an inkjet printer.
	-Liquid resins and gels -Photopolymers	3D photografting	Micro-level designs are traced using lasers in the photopolymerisation process. The technology has medical applications such as the growth of living cells and tissues artificially.
		Stereo Lithography (SLA)	Lasers transform liquid to solid parts.
Digital Light Processing (DLP)		Selective exposure of light on liquid polymer in a container occurs via a DLP projector. Consequently, the liquid solidifies to create layers. Excess liquid polymer is then drained out.	

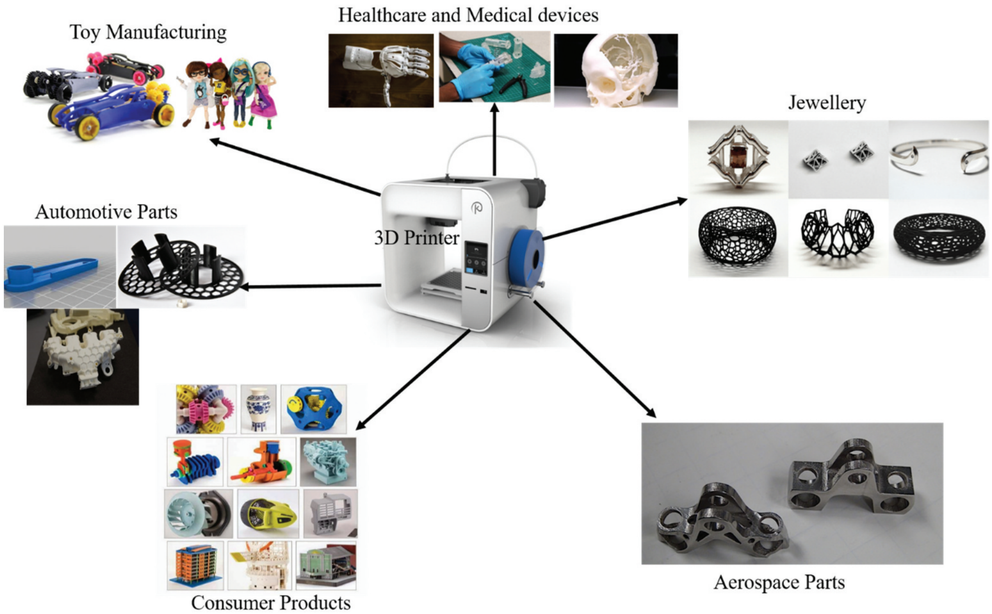

Figure 1. Applications of 3D printing technology. Adopted from [7,8].

manufacturing, environmental sustainability, environmental effects and pollution from additive manufacturing. The search was limited to the last decade (2011–2021).

2. Recent advances and applications of 3D printing technology

There are several additive manufacturing techniques depending on raw materials used and the fabrication processes applied. The techniques and their latest applications are as shown in Figure 2. The techniques can be categorised into four: 1) extrusion-based printing, 2) droplet-based printing, 3) vat polymerisation-based printing and 4) powder-based printing [10]. Extrusion-based printing applies techniques such as FFF and FDM to squeeze out composite material or thermoplastics from a hot extrusion head with a nozzle to add materials in layers and at vertical or horizontal orientation based a machine tool, which is controlled numerically [11]. The technique is used in bioprinting, polymer and metal printing [12]. Advances in the technique include multiple heads extrusion, precise extrusion deposition and precise extrusion manufacturing [13]. These advances are useful in medical applications, particularly the production of bone, soft tissue and vascular models [10]. The droplet-based printing, also referred to as the material jetting technique, uses liquid material whose droplets are released and then selectively polymerised as directed by ultraviolet light to manufacture structures [14]. It could be in the form of aerosol-, poly- and binder-jet printing (AJP, PJP and BJP). In the vat-polymerisation processes such as SLA and DLP, light-specific hardening and light-curing resin material moulding is applied to fabricate intricate parts such as fluidic interconnects, valves and lenses [15]. Powder-based printing using the SLS, SLM, DMLS and EBM applies local heating to melt metallic powder and use it to fabricate customised porosities, internal shapes and external structures [10].

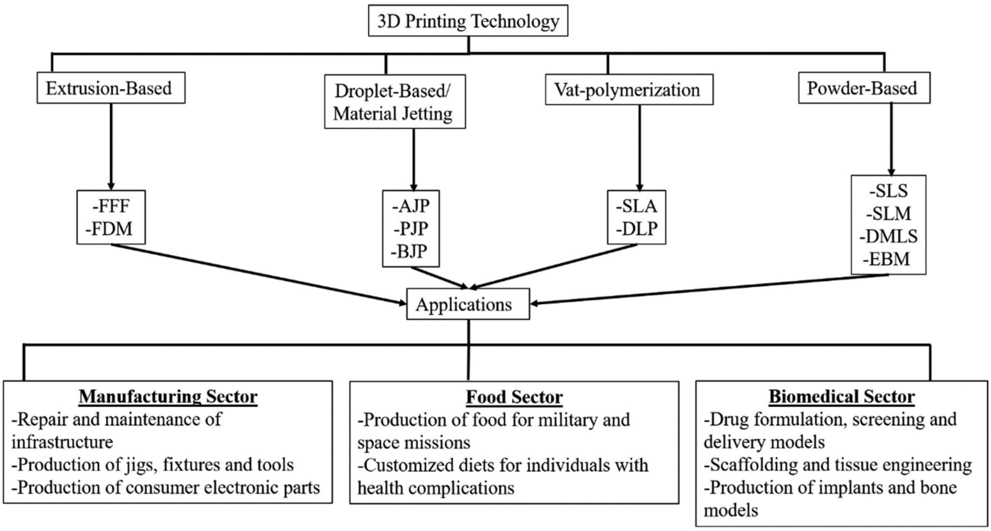

Figure 2. Classification of the techniques of additive manufacturing and their most recent applications.

The 3D printing techniques have gained various applications in recent times. In the medical field, they are useful in drug formulations, production of medical instruments and models as well as in tissue engineering through manufacture of scaffolds [10]. By combining advances in 3D printing with technologies in genomics, imaging and data analytics, insertion of implants in patients, controlled drug delivery and implementation of drug screening models is easy [16]. Using coffee, soya, malt and winery wastes and 3D technologies of SLS and FDM, polyhydroxyalkanoates useful in biomedical applications have been produced [17]. In the military sector, additive manufacturing has enabled the creation of assorted meals that are difficult to acquire in battlefields, have a variety of ingredients and are in customised packages [18]. For individuals in space missions, the technique is hardy in producing safe, acceptable and nutritionally suited foods using minimal spacecraft resources [19]. For individuals with difficulties in chewing, swallowing, allergies and with nutritional intolerances, 3D printing has enabled customised food production to suit their needs [20,21]. Manufacturing applications of 3D printing technology have advanced to production of consumer electronic parts, automotive construction of bridges, in the repair and maintenance of transport infrastructure and in the production of tools, jigs and fixtures used in medical applications [22]. The applications of the technology are continually evolving and their scope widening to other fields apart from the manufacturing sector.

3. Environmental impacts of 3D printing

The environmental impacts of additive manufacturing can be categorised based on four considerations: 1) resource use, 2) energy use, 3) waste and 4) emissions. Depending on the impacts considered during assessment and the manufacturing technique being replaced by 3D printing, negative or positive environmental impacts could be reported. For instance, 23,established that 3D inkjet printers had high negative environmental impacts compared to conventional computer numerical control (CNC) machining during mass production. A comparison of CNC with FDM 3D printing showed that the latter had lower negative impacts. Injection moulding method had the lowest negative environmental impacts compared to FDM and CNC approaches [23]. Another study found that selective laser melting (SLM) was ecologically friendlier compared to conventional machining during the production of aerospace and automotive parts [25]. Specific categories of environmental impacts of 3D printing are discussed in subsequent sections.

4. 3.1 3D printing and energy use

Energy use in 3D printing remains one of the most contested factors with some authors praising the technology as energy efficient, while others suppose it to be high-energy consuming [4]. Energy consumption by additive manufacturing occurs at industrial, retail and consumer levels [2]. At the industrial level, consumption has advanced from rapid prototyping and mould making to continuous manufacturing of lightweight aerospace and automotive parts. At retail level, printing shops offer printing services continuously while using renewable energy or cheap energy supplies. At the consumer level, desktop 3D printers are used sporadically though the use is expected to increase as the technology and its uses become widely recognised. Maximum use of printers in a centralised approach compared to intermittent use and use of minimum printers to do maximum number of printing tasks is less energy consuming and environmental friendlier and vice versa [23]. Depending on the printing technology, granular material binding 3D technologies are energy inefficient compared to FDM that do not require a pre-heating process [26]. The use of laser metal deposition for instance in 3D printing saves approximately 115.7 TBu annually [27].

Factors such as the processing speed, type of material used, layer thickness and build volume influence the energy consumed for 3D printing. Faster processing speed printers, materials workable at low temperatures, larger layer thickness and printers of high build volume that can produce multiple parts are more energy saving [4]. Since 3D printers are not designed to be energy efficient according to 28, it is prudent to produce lighter products to save energy and hasten production [29]. Using high-end technologies in the preheating, printing and cooling processes of printing is recommended to reduce the energy consumption according to 6. To optimise knowledge and understanding of the environmental impacts of 3D printing technology on energy consumption, life cycle assessments supported by adequate data are required as 4,advised since pre-existent data is inconclusive.

4.1. *Materials and material waste for 3D printing and their environmental impacts*

Materials used in 3D printing differ based on the technology used as shown in Table 2. The technology is, however, limited by the variety of materials that can be used in one print. Additive manufacturing is also limited to producing materials that can conduct electricity such as electronic components and pyrex-made cookware unless using conductive ink adaptive to limited 3D printers [30]. Unless high-end commercialised, most printers cannot compile different materials in one print [31]. Additionally, they cannot mix colours of the same material to produce one print.

The environmental impacts of various 3D printing materials has been studied over time. The use of PLA, which is biodegradable and corn-based, is becoming typical due to the low heat and energy requirements, reduced shrinkage, better print quality and reduced emissions associated with the material hence environmental friendly [32]. However, due to its low melting point, its durability and strength are lower compared to ABS in addition to being costlier [33]. The use of recycled plastics in 3D printing has been hailed as an environmentally friendly breakthrough considering the slow or non-biodegradable nature of the material [34]. The recycled plastics are ground and through extrusion made into new filaments. [4] also noted that waste material produced during 3D printing can be recycled into new filaments. Although research is ongoing on the energy requirements of the process and the physicochemical changes of the recycled plastic, it is evident that recycling would save on the cost of purchasing filament in addition to preventing environmental pollution [34,35]. The use of wood-based composites that have similar properties as wood, including ability to paint, cut or sand in additive manufacturing, has been studied owing to its low-energy requirements, cost-efficiency and its green nature compared to glass and carbon filled polymeric materials [36,37]. The use of metal powders is associated with low material use, minimum material wastage, and low-energy use [38]. Additionally, metal 3D printing has made it possible to produce complex shapes using less material and in the aeronautical industries where more than 40% reductions in aircrafts have been achieved with the technology [27].

Material waste during 3D printing is in the form of print supports and beds used in producing complex geometries. According to 31, the waste could be even more compared to the final product depending on the printing orientation and geometry. Generated waste depends on the printer used, where FDM technologies have been found to produce lower waste quantities compared to inkjet without considering the support material [23,26]. For instance, the use of metal mutants in automotive industries that are lighter was confirmed to be greener in that it used low feedstock and low energy in addition to producing zero wastes [39]. Metal sintering technologies are preferred for massive production since they involve layer fusion and save on material use for support [33]. At the use phase, metal sintering products minimise fuel demands if used for aeronautical and automotive applications [31].

5. 3.3 3D printing and air pollution

The expansive use of additive manufacturing for industrial, research and domestic purposes is a threat to air pollution [40,41]. During extrusion of 3D printing material, volatile organic compounds (VOC) and ultra-fine particles are produced. Some of them have negative human health and environmental effects. The VOC results from thermal degradation of additives and polymers and their extrusion during binder jetting and FDM as experimentally confirmed by 42,43, and. No standard procedures, however, have been established to assess how aspects such as the printer model, the filament colour, extrusion temperature, and material type influence the emitted particles [24]. Nano particles, gaseous material and particulate matter, which have negative effects are also produced from 3D printing [44, 45]. The emissions occur during the printing process and have been reported in the FDM technology through a series of experiments [4]. ABS and PLA techniques also produce emissions and particles that are harmful to pets and persons susceptible to allergic reactions [31]. To reduce the effects of emissions, high efficiency particulate air filters and ventilation systems in enclosed 3D printers are preferable. Additionally, printing materials that are green such as non-toxic thermoplastics should be adopted in the technology.

6. Minimising the environmental impacts of 3D printing

In this short review, the evaluation of the impacts of 3D printing on the environment is at the nascent stage and can only be qualitatively assessed. This is because life cycle assessments on these aspects are yet to be comprehensive due to limited data. However, a number of studies have proved that additive manufacturing enhances environmental management, particularly the reduction of fuel consumption [4] and reduced carbon dioxide emissions, compared to conventional manufacturing approaches [46]. The technology also has negative impacts on the environment including production of waste, high-energy consumption, production of emissions and particulate matter that lead to air pollution. To reduce the negative environmental impacts of 3D printing a number of suggestions have been made.

First, the printing time per product and ultimately, energy consumption can be reduced significantly by maximising the build volume of the printer used to fasten the printing process and using hollow parts to avoid material wastage caused by solid supports and beds. Additionally, optimising the orientation to reduce material wastage and enlarging the layer thickness to reduce energy consumption and enhance geometric tolerance and surface finish of the prints is recommendable [47]. Reducing the standby and idling time by using the minimum number of printers for maximum activity reduces non-active energy impacts [2]. Optimising the melting point of printing material, avoiding additions to the printed product and choosing materials of low emissions and reduced shrinkage is crucial in alleviating resultant environmental impacts [29]. The preference of materials sourced from recycled plastics or biodegradable and renewable sources such as PLA contributes positively to environmental protection [28,32]. Metal wastes, which are highly recyclable, have been used in 3D printing technology towards eco-friendliness and are most preferred in an optimal circular economy [48]. Examples include titanium, nickel alloys, stainless steel, copper and magnesium wastes as well as rare earth metals [49]. To avoid wastage, 3D printer settings should promote the best-quality products by choosing the print model and technology with the lowest waste production and recycling of support or low-quality product waste to new filament [26]. The use of recycled plastics to make new filaments is also suggested [35]. Purchases of feedstock should be done from suppliers that offer waste return services.

7. Conclusions

This mini-review focuses on the environmental impacts associated with additive manufacturing. It was observed that 3D printing technology has both positive and negative impacts. Positive impacts are associated with reduced production of wastes, ability to recycle and reuse 3D printing waste material, ability to use wastes from malt, wineries and plastics reducing pollution, low-energy use and emissions due to on-demand manufacturing. Negative impacts include production of particulate matter and volatile organic compounds as well as waste production depending on the 3D technology and materials used. Using empirical evidence, both positive and negative impacts of the technology have been realised depending on the printing technology used, the technology that is being replaced by 3D printing, the material used, the settings of the printer and the volumes targeted for production. Metal additive manufacturing was found to be the most suitable for an optimised circular economy due to its high recyclability. The adoption of metal 3D printing is therefore recommended. Intensified research is also essential to ensure that the adopted 3D printing technology advances in the near future promote environmental sustainability through processes and product optimisation. The mini-review also draws attention to researchers, 3D printing technology developers, users and consumers to focus on the quantification and assessment of the environmental impacts of additive manufacturing using empirical evidence to enhance the understanding on the topic and manage the negative impacts that are contributors to climate change.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

F.M. Mwema http://orcid.org/0000-0001-6116-5587
TC Jen http://orcid.org/0000-0003-1743-4668

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