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REVIEW ARTICLE

Sustainable considerations in additive manufacturing processes: A review

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ABSTRACT - Efficient waste management practices are becoming increasingly necessary due to the negative environmental and health impacts of waste generation and disposal. One type of waste that has received particular attention is electronic waste (e-waste). This category of waste has the potential to cause significant environmental harm if not disposed of properly. The management of e-waste is crucial in the electrical/electronic industry which has led to the creation of models and institutional legislature to promote sustainable production processes. Among these processes, Additive manufacturing otherwise referred to as 3D printing is particularly effective in reducing waste generation and energy requirements by reusing spent parts and products as feedstock. Sustainability in the manufacturing and production sectors can be promoted through the inculcation of certain practices. Of these practices, reusing e-waste that would otherwise be disposed of in landfills has the potential to promote environmental cost savings. This article introduces the potential of e-waste being integrated into the manufacturing sector to promote sustainable production. The article also addresses the problem of geometric e-waste generation and suggests an efficient way of reusing waste from the electrical and electronic industries.

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1. INTRODUCTION

The application of additive manufacturing (AM) to industrial processes has over time begun to receive much-needed attention. The most applied additive manufacturing method is 3-dimensional (3D) printing. In certain cases, the term 3D printing is used interchangeably with additive manufacturing. 3D printing is an additive manufacturing technology that employs computer-created designs to create a 3-dimensional part in layers. The merits of additive manufacturing include the ability to produce items with complex geometries, relatively low setup cost, simplicity of design and operation, and low tooling cost [1]. 3D printing has been adopted across several industries not limited to automobiles, biomedicine, bioengineering, aerospace, electronics and the construction industries. A major application of 3D printing is rapid prototyping. This technique refers to technology and apparatus for fabricating physical objects directly from parts created in computer-aided design using additive layer manufacturing techniques without the requirements of process planning [2]. According to Abdulhameed et al. [3] additive manufacturing processes can be classified based on several factors including the dimension of the machine, nozzle specification, and production speed. However, the major classification of this production process is chiefly based on the input material. 3D printing technology is an attractive technology capable of reproducing an existing part at a lower cost and with minimal process requirements. The advent of AM technologies has provided manufacturers with a more cost-effective and environmentally friendly option in the production of parts and components devoid of traditional geometric constraints [4]. In AM technologies are capable of producing parts and components with minimal material waste and relatively low energy requirements compared to conventional manufacturing processes. Despite the numerous merits of additive manufacturing not limited to limited power requirements, cost-effectiveness and limited material stage among others, AM technologies are plagued by issues such as low production rates [5], limited choice of materials, and dimensional inaccuracies [6]. To mitigate against some of the highlighted limitations of AM technologies, research has gone into optimizing the production processes to mitigate against the prevailing technological issues. Ergene et al. [7] investigated the effect of layer height and test temperature on the energy absorption of PET-G parts. From the study, it was observed that the effect of the layer height was more dominant than the test temperature for energy absorption. It was also gathered that the increased hardness was a result of lower layer height while increased tensile strength was brought about by increased layer height. Ergene et al. [8] investigated the mechanical performance of 3D-printed ABS pipes with varying cellular wall designs. Four designs were considered, fully solid pipe, hybrid pipe, honeycomb pipe and rib pipe to be investigated for mechanical properties including compressive strength, specific compressive strength, elastic modulus, specific modulus, energy absorbed and specific energy absorbed. It was observed from the investigation that a fully solid pipe produced the best mechanical properties due to its total weight and high fill rate compared to the other designs. Ergene et al. [9] investigated the effect of layer height, infill rates and tapered angle on the vibration behaviour of PET-G tapered beams produced using the fused filament fabrication method. From the study, it was gathered that the tensile strength and elastic modulus decreased with the layer height and increased with increasing infill rate respectively. It was recommended that the study outcome can be used as a reference during the design of parts to be subjected to vibration.

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As stated in the Handbook for Sustainable Consumption and Production [10], the concept of sustainable consumption and production attempts to improve the quality of life without increasing environmental degradation, reducing the material/energy intensity of economic activities without compromising the resources necessary for future generations to thrive. Figure 1 depicts the processes involved in sustainable consumption and production. Among the stated advantages, the issue of environmental sustainability is a driving force towards the adoption of 3D printing as a means of product manufacturing. There are several positive environmental benefits of additive manufacturing processes compared to traditional manufacturing. Chiefly among the existing benefits is the considerably reduced waste generated in 3D printing. The waste reduction is a result of the manufacturing method which produces the required part through layer deposition of material compared to traditional manufacturing technologies which create parts by material removal. Despite this recorded environmental cost-saving process of product development through 3D priming techniques, there is still ongoing research in this area that is focused on energy use, emissions and material utilization for the production of a part/component.

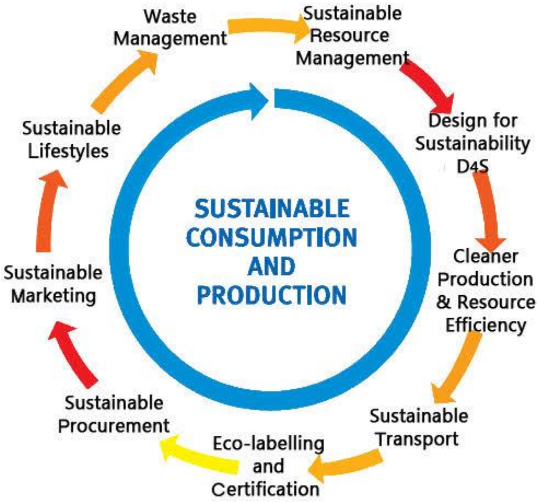

Figure 1. Processes in sustainable consumption and production according to the UNEP [11]

Waste minimization and the reduction of greenhouse emissions are the core framework of the circular economy [12]. In terms of the application of the circular economy framework proposed by the European Commission, several tools have been deployed taking into account production processes that cater for raw material acquisition, production, consumption and waste management [13]. The major area of concentration on the topic of sustainability is waste reduction. This is currently achieved through the utilization of the 3 Rs of sustainability which are, reduce, reuse and recycle. The research into ways of sustainable production through 3D printing is currently adopting methodologies that imbibes the philosophy of sustainability.

2. ELECTRONIC WASTE

In the context of parts and products that have outlived their useful life, waste can be regarded as unwanted materials which could be a by-product of any production process or domestic activity. Permanent waste disposal occurs in situations where a material loses its inherent worth or value. According to the United Kingdom government [8], waste can be classified based on its source as depicted in Figure 2.

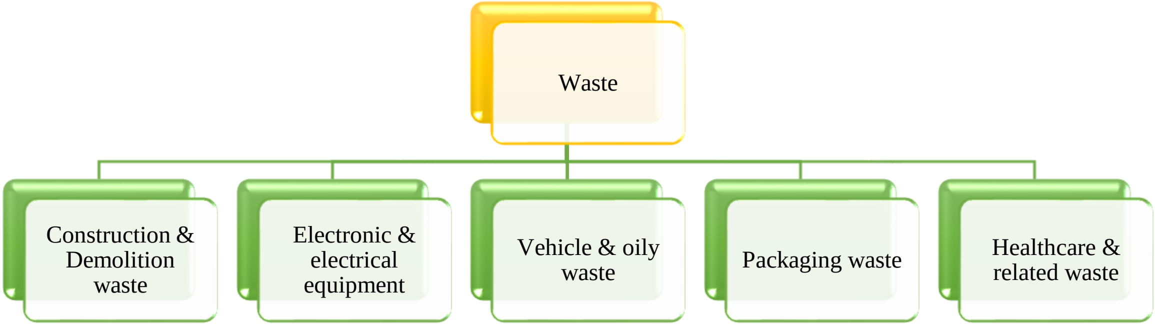

Figure 2. Classification of waste

Also referred to as Waste Electrical and Electronic Equipment (WEEE), e-waste is obtained for electronic products that are designed to be used with a voltage not exceeding 1 kV and 1.5 kV for alternating and direct current respectively. e-waste as its name suggests is a classification of waste generated through the utilization of equipment or products that are powered by electricity. According to the California State Government, e-waste is generated from electronic products nearing the end of their useful life [14]. This classification of waste includes electronic equipment such as computers, radios, television sets, printers, mobile phones, scanners, fax machines, refrigerators and microwave ovens. Due to the nature of e-waste, disposal has become a serious problem worldwide. Current disposal means of e-waste include acid baths, incineration and landfilling [15] Global e-waste generation has been estimated to be 53.6 million metric tons in 2019 alone [16]. It was also highlighted in the same report that the figure indicates a 21 % increase since 2014. The current state of e-waste generation has been attributed to the advancement in technologies which has not only increased the utilization of new and improved electronic products but made the existing products obsolete. In so doing, where no channel for reuse and redesign exists, these older models are disposed of. The global generation of e-waste is summarised in Figure 3.

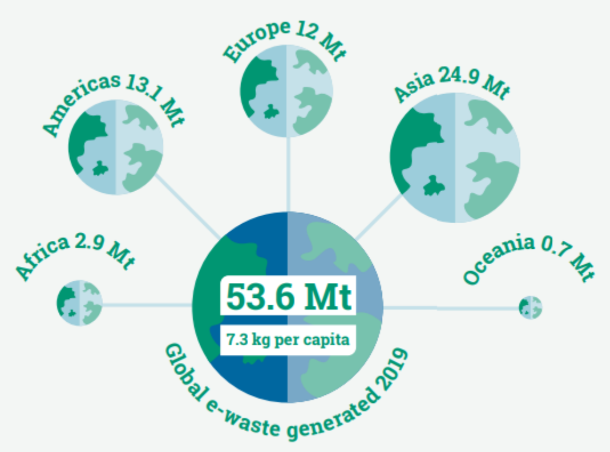

Figure 3. Global generation of E-waste [17]

Hazardous Materials such as mercury, arsenic, and cadmium have increased the already existing concerns with the disposal of e-waste [13]. The presence of these toxins has negative impacts on the ecosystem (air, water and soil) and humans. There has been recorded indiscriminate disposal of e-waste in water bodies which are responsible for the alteration of marine p/h values, toxification and eventual death of marine life. Improper disposal of e-waste in landfills is responsible for the introduction of toxins that contaminate underground water and vegetation in the surrounding area. Hazardous materials present in improperly disposed e-waste can cause human birth defects and diseases capable of affecting vital organs. The effects of these toxins on human health have been summarised in Table 1.

Table 1. Effect of selected toxins generated from e-waste on humans [14–18]

Toxin	Source	Adverse Health Effect
Mercury	Batteries, thermostats, cell phones, fluorescent bulbs, chest freezers, washing machines	Kidney failure, brain damage, liver problems, respiratory problems, skin cancer and reproductive issues. It also affects the development of a foetus.
Arsenic	Circuit boards, LCDs, computer chips	Respiratory issues, nausea, skin rashes, liver and kidney damage, reduction of red blood cells, vomiting, lung infection.
Cadmium	Resistors, corrosion-resistant alloys, nickel-cadmium batteries, PCBs, semiconductor chips, cell phones, batteries, printer toners	Renal failure, brain disorders, kidney damage, neurological damage, mental problems, hearing impairment, lung disease, and bone disease.
Lead	Cathode ray tubes, printed circuit boards (PCBs), televisions, plastic housing	Kidney failure, reproductive organ damage, damage to the central and peripheral nervous systems, intellectual impairment, reproductive problems, and blood infections.
Poly Vinyl Chloride (PVC)	Protective casing for a variety of electronic devices, cable coating	Incinerating PVC leads to reproductive anomalies, infertility, neurological problems, and endocrine disruption.
Chromium	Corrosion-resistant films, memory tape discs, cables, hard disc components	Exposure can lead to irritation of the throat and lungs, lung cancer, immunosuppression, dermatitis, asthma, and DNA damage.

Table 1. (cont.)

Toxin	Source	Adverse health effect
Brominated Flame Retardants	Circuit boards, power supply boxes, most polymeric casing for electronics, televisions	Cancer, loss of neurologic function, reproductive problems, immune issues, and endocrine disruption.
Beryllium	Cathode ray tubes, power supply boxes, circuit boards, power supply boxes	Lung disease, lung cancer, chronic beryllium disease, nervous system damage, liver problems, and heart and lung disease.
Nickel	Batteries, PCBs, cables	Skin damage, lung infection,
Antimony	Semiconductor components, circuit boards	Skin irritation, hair loss, lung and heart damage, fertility problems, and gastrointestinal failure.

According to Ogungbuyi et al. [18], the increase in the quantity of e-waste in developing countries can be attributed to factors such as low awareness of waste management, high influx of refurbished goods, and low expertise in the repairs of damaged electronics. Nigeria in the context of a developing country has inefficient general waste management policies and methodologies. Issues also bothering this problem include the non-categorising of the different classes of waste. Currently, e-waste is disposed of together with municipal solid waste which eventually leads to the side effects already highlighted in Table 1. It was estimated in 2018 that Nigeria generated 43.2 million metric tonnes of waste annually of which this figure is expected to rise to up to 72 million metric tonnes by 2025 [19]. It was also highlighted that roughly 10 % of that figure was generated as e-waste in 2019 of which only roughly 1.8 kg have been reused or recycled [20].

To address the issues that stem from the ever-growing environmental and ecological degradation and adverse climate change, certain governments have begun legislative procedures to address the underlying issues. To this effect, several governments around the globe have begun to enact policies that present achievable plans to deal with the ever-increasing growth of electronic waste to better deal with the resulting issues, The Environmental Protection Agency (EPA) has begun programs such as the International E-Waste Management Network (IEMN) which was set up to strengthen the national initiatives and enhance regional cooperation in electronic waste management. In 2010, an Interagency Task Force on Electronics Stewardship was initiated to enhance the management of electronic waste by increasing the demand for recycling through incentivization, reducing harmful exports of e-waste and finally building capacity in developing countries [21]. In Nigeria, the National Environmental Standards and Regulations Enforcement Agency (NESREA) has constituted a task force in cooperation with other agencies such as Nigeria Customs to stop the illegal dumping of WEEE [22, 23]. In Ghana, e-waste legislation was constituted in 2016 to provide a framework to control, manage and properly dispose of e-waste to curb environmental and health-related issues brought about by its inadequate disposal methods [24]. The Indian government has established the extended producer responsibility concept that works by assigning mandatory responsibility to all related stakeholders to develop sustainable collection methods, create environmental awareness programs and develop material recovery systems [25].

E-waste management has the potential to be a major driver in the vision that is the circular economy. This is why there have been worldwide legislations towards the proper handling of this category of waste. Generally, these legislations have tilted towards the application of the 3Rs (reduce, reuse and recycle) of sustainability generally referred to as the 3 pillars of sustainability. In addition to safer means of disposal, the generation of e-waste could be reduced through other means. Electronic equipment could be sold or donated and in cases where electronic products or parts cannot be repaired, recycling should be encouraged. In light of the aforementioned issues and concerns, there have been numerous interests in the reuse of e-waste by way of research endeavours. These endeavours have recommended potential areas where e-waste can be used. Recommendations have been made that proffer solutions in both the advancement in sustainable production and utilization of parts and products and in some cases cost reduction.

3. SUSTAINABILITY OF E-WASTE MATERIALS

The highlighted issues with the disposal of e-waste have prompted global efforts that intend to find alternative uses and applications for these waste materials. To this effect, the introduction of the circular economy has received numerous attention as evident in the succeeding sections of this work.

3.1 Circular Economy

The circular economy model aims to tackle global challenges such as climate change, losses in biodiversity, waste and environmental pollution. The initiation and implementation of the circular economy are based on the elimination of waste and pollution, circulating products and materials and the regeneration of the biosphere. As illustrated in Figure 4, the conventional value chain of product development involves a cradle-to-grave approach in the manufacture of commodities. This approach does not take into consideration the impact of the disposal of products that have outlived their useful lives. In contrast, the circular economy framework proposes a cradle-to-cradle approach where considerations for the reuse of these products that have 'outlived their usefulness' are sought through their valorisation. In the concept of WEEE, the introduction of the circular economy will offer immediate solutions by performing the tasks of extending product life cycles and recovering functional and material value from e-waste [26]. Figure 4 shows the difference between the linear and circular economy as it concerns the development and use of products.

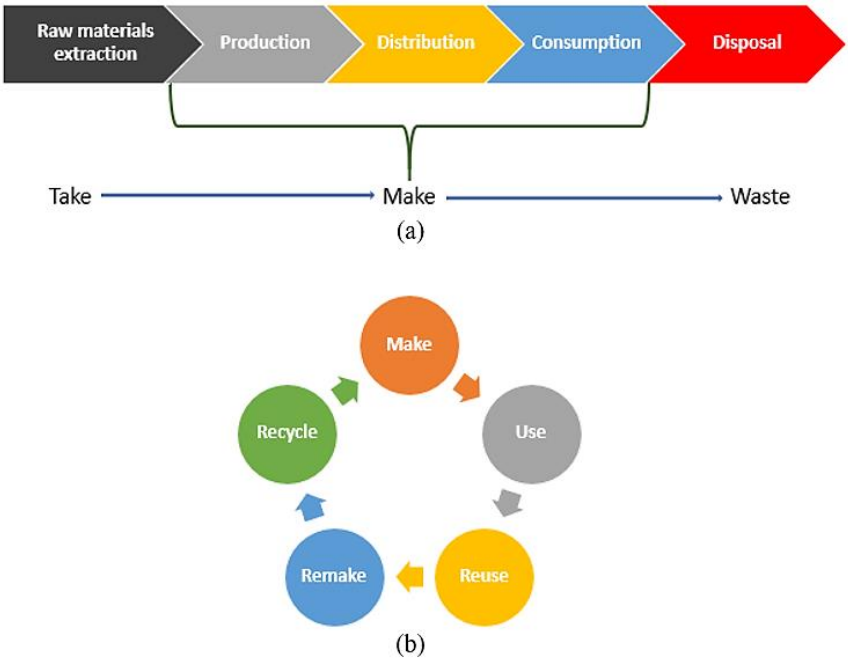

Figure 4. (a) Linear economy and (b) Circular economy

The application of sustainable production of parts and products is being sought after as a means to reduce energy requirements of production, cost reduction, and environmental sustainability. Successful implementation of sustainable production has been highly successful in the reuse of metals, particularly aluminium. According to the European Aluminium Association, 75 % of the entire aluminium ever produced can be recycled, which requires approximately 8% of the total energy required to produce virgin aluminium [27]. Other applications in sustainability have been implemented across several endeavours in the reutilization of waste materials to produce parts or stock items including metal matrix composites [28–30], solar energy applications [31, 32], and in the construction industry where plastics from e-waste such as acrylonitrile butadiene styrene (ABS), polyamides (PA), polycarbonate (PC), printed circuit boards (PCBs), and high impact polystyrene (HIPS) have been utilized to reinforce concrete [33–35].

The requirements for sustainable application of e-waste as already established in the preceding section of this work are on the rise as a result of the increasing quantity of the e-waste, presence of toxins, contamination of the immediate vicinity of the landfills and adverse health effects to people close to this waste. Legislatures in developed countries such as the United States of America and other parts of Europe have been passed for the appropriate management of E-waste. Per the 3 pillars of sustainability, as in the case of other classifications of waste, e-waste can be more sustainable with the application of the 3Rs (reuse, reduce and recycle). In addition to the environmental impact of e-waste, studies have indicated that electrical/electronic waste is embodied with up to 69 elements within the periodic table [17]. Issues bordering towards the depletion of natural reserves, and fluctuations in market prices have deemed it important for product developers to look into sustainable avenues to harvest certain precious metals. In the bid to curb the issues associated with e-waste disposal and under-utilization, firms like Mint Innovation located in Auckland New Zealand have taken certain measures to utilize environmentally friendly means to harvest precious metals from e-waste [36].

To address the issues that emanate from the ever-growing environmental, and ecological degradation, and adverse climate change, governments around the world have begun legislative procedures to address the underlying issues. Consequently, several governments worldwide have begun to endorse policies that lay out achievable plans to deal with the ever-increasing growth of electrical e-waste. According to Forti et al, "as of October 2019, 78 countries have either a policy, legislation, or regulation governing e-waste in place. With this endeavour, approximately 71% of the world's population is currently covered." [17]. To better deal with the issues, The Environmental Protection Agency (EPA) has begun programs such as the International E-Waste Management Network (IEMN) which was set up to strengthen national initiatives and enhance regional cooperation in electronic waste management [21]. Policies such as extended producer responsibility (EPR), a principle in the management of e-waste that has been introduced as environmental policy in several nations. This policy is a method of integrating sustainable development principles such as the creation of an incentive mechanism that enhances lifecycle consideration and prioritization of preventive measures for industries to improve their production processes [37]. This policy has been put in place basically for the producers by making them more aware of their responsibilities to the customers using their product. The policy also reiterates that the environmental responsibility of the producers goes beyond the end-of-serve life of their products. The EPR methodology was fundamentally designed to shift the responsibilities of sustainable production and environmental cost savings to the producers and provide certain incentives to intensify efforts in this regard. According to Langrova, the main goals of the EPR include waste prevention and reduction, decreased consumption of natural resources, energy recovery processes, and incorporation of recycled products into the production of new items [38]. In 2010, an Interagency Task Force on Electronics Stewardship was set up to enhance the management of electronic/electrical products by increasing the demand for recycling through incentivization and the reduction of harmful exports of e-waste, and finally building capacity in developing countries [21]. In Nigeria, the National Environmental Standards and Regulations Enforcement Agency (NESREA) has set up regulation S.I No 23, 2011 which principally works to prevent and minimize pollution from operations relating to the electrical/electronic sector [39]. The establishment of this regulation is based on the 5Rs which are reduce, repair, reuse, recycle and recover. In addition, NESREA has constituted a task force with the cooperation of other agencies to intensify efforts to curb the illegal shipment of e-waste while creating awareness of the prevailing issues caused by the mishandling of this class of waste [40]. In Ghana, e-waste legislation was constituted in 2016 to provide a framework for control, management and proper disposal of e-waste to curb environmental and health-related issues brought about by its inadequate disposal methods [24]. There is ongoing research in the reuse of e-waste in several industrial endeavours. Several works done in this regard are described in Table 2.

Table 2. Successful research involving the reuse of e-waste

S/No	E-Waste	Source	Application	Reference
1.	Polycarbonate	Air conditioners, refrigerators, food mixers and hair driers	Useful as a biomaterial for tissue engineering applications	Ghosal et al. [41]
2.	Printed Circuit Board, plastic, LCD Monitors	Laptops, radios, mobile phones, television sets	Coarse aggregate in construction	Dixit et al. [42]
3.	Cathode ray tubes (CRT)	Computer monitors, television sets and radar equipment.	Cement mortar and paste for the construction industry	Yao et al. [43]
4.	Waste glass	Scanners, photocopiers, and printers	Concrete	Nasier [44]
5.	E-Plastic	Television sets, mobile phones, photocopiers, scanners, laptops, routers, and water dispensers.	Binders for the production of concrete for the construction industry.	Goh et al. [45]
6.	E-Plastic	Shredded printer casings	Filaments for 3D printing.	Gaikwad et al. [46]
7.	Cathode ray tubes	Computer monitors, television screens and luminescent lamp glass.	Foam glass for petroleum and chemical industries, underground engineering, and military defence. Ceramic glazes.	Guo et al. [47] Chen et al. [48] Lazau et al.[49]
8.	Electronic cables	Laptops, television sets, radios, printers.	Ornamental design and interior accessories.	Fanthi et al [50]
9.	Printed Circuit Board (PCB) and E-plastics	Laptops, television sets.	Polymer Matrix Composites	Venkatakrishnan et al. [51]
10.	Lithium batteries	Lithium batteries	The graphite anode from the waste lithium battery was repurposed for the production of an advanced cathode for lithium-based dual-ion batteries.	Yang et al [32]
11.	Waste electrodes	Supercapacitors that have reached their end-of-service life.	Regenerating carbon powder from waste electrodes for application in supercapacitors.	Zhang et al. [52]

4. 3D PRINTING TECHNOLOGIES

3D printing is an additive manufacturing technology that is used in the production of 3-dimensional parts directly from a computer-aided design (CAD) design. It entails the manufacturing of a part by adding layers upon layers until the final part has been produced. To create a part using 3D printing, a CAD model is generated and saved as a stereolithography file (STL) before a post-processing operation referred to as slicing. Slicing in this context is the use of computer software to convert the CAD model into instructions compatible with the 3D printer. These instructions are required for the 3D printer to manufacture the required part. 3D printing technology was introduced to perform the function of rapid prototyping hence, earlier iterations of this technology were referred to as rapid prototyping. Some 3D-printed parts are shown in Figure 5.

Figure 5. 3D printed parts [53]

As opposed to subtractive manufacturing technologies more commonly known as traditional machining, 3D printing offers several advantages including mass customization, flexibility, rapid prototyping, production of lightweight parts and components, automation, lower energy demand and cost, waste minimization, and environmental cost savings [54–57]. Despite these merits, there are drawbacks such as limited starting materials, post-processing requirements, issues relating to mass production and design inaccuracies [6]. The highlighted merits of 3D printing technologies have ensured that subcategories of this technology are steadily being researched to improve the process. Industrial applications of 3D printing include aerospace, automotive, food, healthcare, construction, electrical and electronic components [58]. Some research endeavours using 3D printing technologies are summarised in Table 3.

Table 3. Research endeavours in 3D printing technologies

S/No	3D printing Technology	Materials	Research	Reference
1.	Fused Deposition Modelling (FDM)	Polylactic acid (PLA) Polyethylene terephthalate (PETG) and Polyhydroxy-alkanoate (PHA).	The study attempted to investigate a suitable thermoplastic material for the manufacture of shield frames. The factors of interest in the study were mechanical properties, geometric accuracy, weight, printing time, filament price, and environmental sustainability.	Zgodavová et al. [59]
2.	Fused Filament Fabrication (FFF)	Biobased blend of polylactic acid and low-cost craft lignin	Characterization of the biobased PLA/lignin blends to investigate the tensile and thermal properties and morphological characteristics.	Gkartzou et al. [57]
3.	Fused Filament Fabrication	Acrylonitrile butadiene styrene (ABS)	The analysis and optimization of the wear properties and characteristics of ABS.	Norani et al [60]
4.	Stereolithography	Photopolymer resin (GP Plus 14122)	Prediction and optimization of the hardness of parts manufactured using SLA.	Hu et al. [61]
5.	Stereolithography	Polyethene glycol diacrylate (PEGDA)	Fabrication of drug-loaded tablets with modifications made to the release characteristics.	Wang et al. [62]
6.	Stereolithography	Ceramic-loaded photo-sensitive resins (25-60wt% alumina, 3 and 8% Yttria-stabilized zirconia (YSZ) and poly(ethylene glycol) respectively.	Low-cost method for the fabrication of advanced ceramics	Varghese et al. [63]
7.	Selective laser sintering (SLS) and Multi jet Fusion	Polyamide 12	Comparison of the manufacture of a specimen produced using SLS and multi-jet fusion technologies. The comparison investigated the physio-chemical characteristics of the powders, mechanical performance and printing characteristics of the printed parts.	Cai et al. [64]

Table 3. (cont.)

S/No	3D printing Technology	Materials	Research	Reference
8.	Selective laser sintering	A mixture of 50 wt.% wheat starch powder, 40 wt.% maltodextrin powder and 10 wt.% palm oil.	Characterization of the novel feedstock for use in food customization. The studies included uniaxial compression test, crack propagation and micro-structural examination.	Jonkers et al. [65]
9.	Polyjet	Photosensitive thermo-plastic resin designated as Vero magenta, Vero white Vero red and Vero grey	The development of an accuracy-based model for the manufacture of parts using polyjet 3D printing technology. This model was designed to increase the quality of printed parts and reduce the number of experimental trials.	Patpatiya et al.[66]
10.	Polyjet	Fullcure 720 RGD material	Experimental investigation into the surface quality of the polyjet 3D printing process. The investigation sought to establish the effect of the deposition angle and blade mechanism on the surface roughness of the process.	Vidakis et al. [67]

4.1 Classification of 3D printing

The different classes of 3D printing differ based on the starting materials the required parts are to be fabricated from, and the materials deposition technique required to build the part layer by layer. The major classification of various 3D printing processes is shown in Figure 6. A brief description of the classes of 3D printing is shown in Table 4.

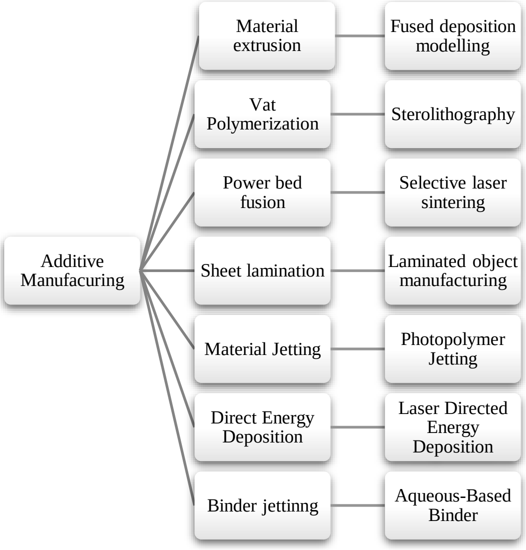

Figure 6. Classification of 3D printing processes based on production principles [68]

Table 4. Classes of 3D printing

Process	Description
Material extrusion	This is a group of 3D printing technologies that requires a continuous thermoplastic filament or in some cases a composite material to manufacture required parts. The feedstock used in this category of 3D printing is in the form of a filament usually stored as spools. The filament is usually fed through an extruder and eventually a heated nozzle where the plastic polymer is then deposited onto the print bed layer by layer until the required item is produced. This class of 3D printing has advantages such as being capable of producing parts from a variety of feedstock materials, relatively easy production technique and lower production costs. Some limitations of this class of 3D printing technology are a high tendency for warping, low dimensional accuracy, delamination and poor surface finish.

Table 4. (cont.)

Process	Description
Vat Photopolymerization	In this class of 3D printing technologies, parts are produced by the selective curing of a photopolymer liquid resin using UV-activated polymerization. The feedstock which is a photopolymer liquid resin is a polymer whose exposure to light results in a change of its properties. The change in the properties is a result of the exposure of the photo polymeric resin to UV light which results in the solidification/curing of the resin that forms the required part. Most processes under this classification have the liquid photopolymers stored in a vat with the platform partially submerged in the liquid surface. This process offers the advantages of higher precision, improved product quality and higher dimensional accuracy. The disadvantages include high initial costs, lower durability and lack of feedstock selections, prolonged exposure to UV light can affect the produced part.
Sheet Lamination	As the name suggests, this category of 3D printing manufactures 3D parts by stacking and laminating thin sheets of material through bonding processes. The thin sheets are usually supplied through a system of rollers unto a platform where the single piece is formed. The completely bonded collection of thin sheets is then cut to produce the required 3D part. The merits of these technologies include lower production costs, ease of material handling, and quicker production time. Demerits include a high volume of waste, postprocessing requirements and bonding inconsistencies.
Power Bed Fusion	In this technique, the heat produced from an electron beam or a laser is used to melt and bond the feedstock materials based on the input CAD model. In this case, the feedstock which could be polymers or metals is powders. This technology has the advantage of being able to manufacture parts with complex geometries. Another advantage of power bed fusion is its ability for mass production. While its limitations include lower surface finishing, increased postprocessing requirements and high capital costs
Material jetting	Material jetting, similar to ink jetting technology manufactures a predetermined part by printing/jetting and curing [69]. The curing process takes place through the application of ultraviolet light or heat. The process of material jetting is conducted by jetting the input material onto a build tray by using a Drop-on-demand process or continuous jetting. As typical with the 3D printing process, the deposited material is printed layer by layer until the required part is produced based on the CAD design. Material jetting technologies are characterised by high levels of accuracy, good surface finish and the use of a variety of starting materials including metals. However, there are certain limitations which include shrinkage, slow production time, and high production costs. Material jetting is widely applied in the production of printed electronics, pharmaceuticals and medicine.
Direct Energy Deposition	Direct energy deposition is a 3D printing process that produces a required part by melting the starting material with the aid of a laser or electron beam. The melted material is deposited layer by layer in a controlled chamber at reduced oxygen levels [70]. This is important to prevent the oxidation of the melted material [71]. In certain cases, a shielding gas creates an inert environment during the printing of a part. Typically 3D printing using the direct energy deposition technology involves a multi-axes nozzle which deposites the melted starting material layer by layer onto a specified surface. The starting materials can be fed either as powders or wires. The powder-based process is relatively more expensive and produces parts with better resolution and surface finish compared to wire-based parts. Wire-based Direct energy deposition is preferred for printing larger parts at higher production rates and lower cost. 3 categories of Direct energy deposition applications exist which include the repair of existing parts, addition of features and production of ner-net-shape parts.
Binder jetting	The binder jetting 3D printing process works by dispersing a liquid agent which acts as a binder onto a powder to form a 2D pattern on a layer [72]. The layers are stacked together to form the required part. The binders are usually of relatively low viscosity. Other characteristics of the powders include packing density, flow ability, droplet viscosity and printing system parameters [73]. The binders are necessary to improve the strength of the part as well are give the produced part its required shape. The powders for this process can be ceramics, metals and polymers. The merits of binder jetting include its ability to produce a part from a variety of starting material powders, the shaping process occurs at room temperature which prevents issues such as oxidation and phase changes [74]. Limitations include post-processing requirements due to curing and densification, lower resolution and high surface roughness, and distorted parts which leads to the production of defective parts.

Some of the most used 3D printing technologies based on reviewed literature are summarised in the succeeding sections of this work.

4.1.1 Fused Deposition Modelling

This process also referred to as fused filament fabrication is one of the most widely used 3D printing technology. This method of 3D printing is a material extrusion process that creates 3-D parts layer by layer using a continuously fed material usually in filament form. The operation of the fused deposition modelling method of 3D printing is highlighted in Figure 7. Typically, in the FDM technology, the filament is forced through a heated nozzle by an extruder which in turn melts the feedstock material to its glass transition temperature. The molten material is then deposited on the printer bed by the nozzle based on the built-part programs generated by the splicer as per the post-processed CAD model. The FDM is particularly built to produce parts from different feedstock including ABS, PLA, PET, and PC. Of these materials, ABS and PLA are the most utilized feedstock in FDM technology due to their ease of manufacture based on their thermal and rheological properties [76]. FDM enjoys wide utilization due to its simplicity, ability to produce a part from a variety of materials, and the ability of the printer to come in various sizes and reduced cost of production due to its absence of specialised tooling requirements. however, there are some limitations to the use of the technology including numerous process requirements which include, environmental factors, working parameters, and machine parameters [77].

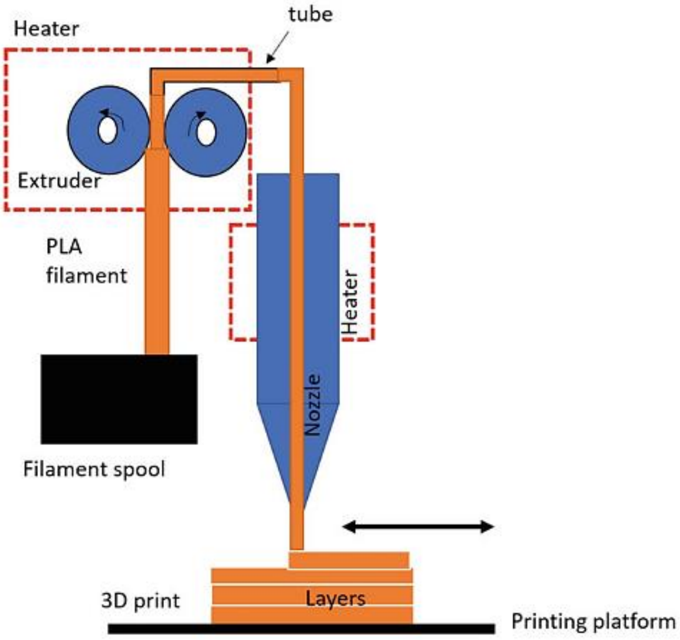

Figure 7. Principle of fused deposition modelling [75]

4.1.2 Stereolithography

SLA is a vat polymerisation or resin 3D printing process where parts are built layer by layer by the local solidification of photosensitive resins through a process referred to as photopolymerization. The general setup is depicted in Figure 8.

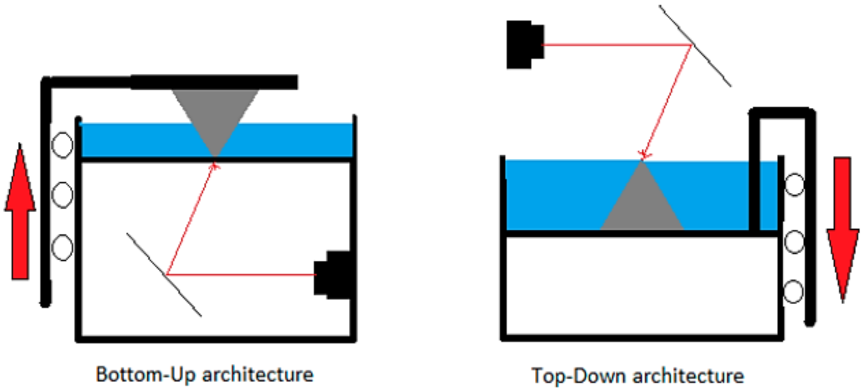

Figure 8. Schematic representation of the techniques used in SLA

SLA is usually employed for parts that require high dimensional accuracy and a good surface finish. The high dimensional accuracy and high surface finish are a trade-off for the higher production cost due to equipment and feedstock material [78]. The cycle time in SLA is dependent on several factors including design complexity, size and feedstock material. Like most 3D printing technologies, producing parts using SLA requires a 2D CAD design of the proposed object to be produced. Which is then post-processed to manufacture the desired part. In SLA, there are 2 major techniques which are the top-bottom and the bottom-top (refer to Figure 8) [76]. In the bottom-up architecture, the UV light source is placed under the resin tank while the part is built upside down. Whereas, in the top-down approach the light source is placed above the resin vat. The build platform begins at the top of the resin vat and moves downward layer by layer until the required part is produced [79]. Defects that are common to SLA include shrinkage, curl distortion, warping and dimensional inaccuracy [78]. Materials used in SLA include standard resins, engineering resins, and bio-material resins.

4.1.3 Specific Laser Sintering

Specific laser sintering is a powder-based 3D printing technology that utilizes a mobile laser beam to sinter heat fusible powders layer by layer until the 3D part is formed based on the input provided by a CAD model. This process is characterized by the deposition of an even layer of powder followed by the sintering operation provided by a high-powered laser beam. The selected powder is sintered by a CO_2 laser. The layer thickness ranges from 80 µm to 150 µm [80]. This process is repeated layer by layer until the required part has been produced. The movement of the laser beam that performs the sintering process is defined by the sliced CAD file which specifies the coordinates the laser beam hits to sinter the layered powders. Figure 9 depicts a typical SLS process.

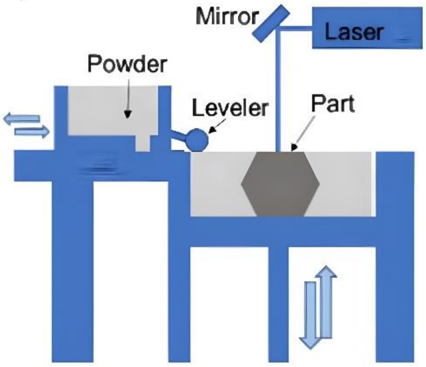

Figure 9. SLS schematic representation [81]

There are 3 categories of SLS manufacturing, solid-state sintering, liquid phases assisted sintering which is used to produce parts from materials that are difficult to sinter. Full melting is usually reserved for ceramic and metallic feedstocks [82]. SLS has the advantage of being isotropic. This merit comes from the sintering process which ensures that the strength is equal in all directions of the applied load [83]. Another major advantage of SLS is its self-support system for powders while manufacturing parts with complex geometries. Manufactured parts have high strength and stiffness. A major demerit of SLS technology is the increased need for post-processing of the produced item. This is a result of the relatively poor surface finish and internal porosity. Feedstock used in SLS 3D printing includes, metals, ceramics, composites, and polymers. Uses of this 3D printing process include functional prototyping, medical devices, and various end-user items.

4.1.4 Photopolymer Jetting

Photopolymer jetting often stylized as polyjet printing is a 3D printing technology which manufactures designed parts by deposition of a photopolymer resin jetted onto a build-tray via inkjet printing. For the production process, the print head injects resin into the build tray corresponding to the build cross-sectional profile. The jetted resin droplets are subsequently cured using UV lamps [67]. The cyclic action of the addition and curing of the layers of photo-resin produces the desired 3D model. Identified factors that affect the quality of the 3D printed part produced through the polyjet method include part orientation, layer thickness, surface finish type and materials [84]. A schematic representation of the polyjet 3D printing technology is illustrated in Figure 10.

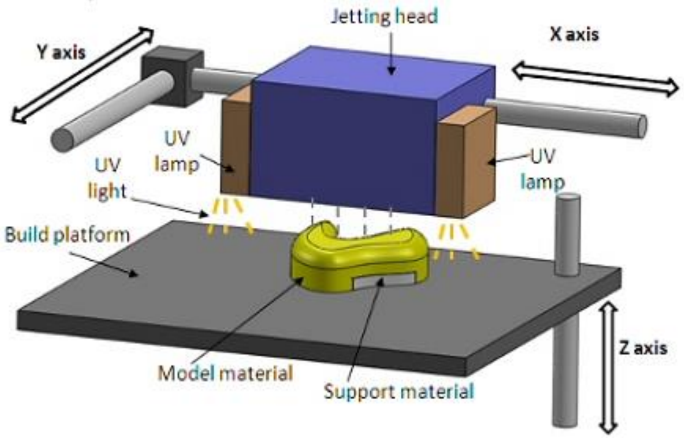

Figure 10. Schematic representation of the PolyJet printing process [85]

Polyjet printing has the advantage of printing more than one material from a single 3D model. This allows for printing models that have different materials, aesthetic and metallurgical requirements. High dimensional accuracy and good surface finishes are also achievable using polyjet 3D printing. Amidst these merits, associated issues of this 3D printing technology are its relative complexity and its restriction to printing only photo-polymeric materials.

4.1.5 Laminated Object Manufacturing

In laminated object manufacturing, a 3D model is produced by stacking layers of thin sheets coated with adhesives that are cut to an outline that corresponds to the cross-sectional shape of the post-processed CAD model. The feedstock materials include metals, plastic and paper [86]. Laminated object manufacturing is commonly used for stylish and visual models that are not suitable for auxiliary implementation [87]. Laminated object manufacturing is characterised by merits such as low lead times, lack of internal stresses, good surface finishing and no support requirement. While demerits include the generation of internal cavities, waste generation and poor accuracy along the Z-axis [88]. A schematic representation of the laminated object manufacturing process is shown in Figure 11.

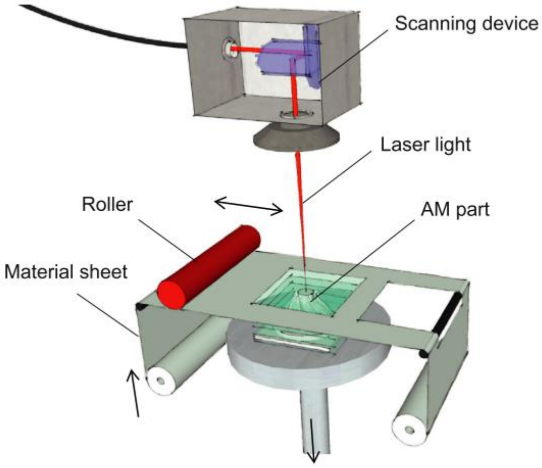

Figure 11. Schematic representation of the laminated object manufacturing process [89]

4.2 Common Materials used in 3D Printing

Currently, the printing of materials such as metal, ceramics and composites is still in its infancy. Research is still ongoing to repurpose 3D printing technologies that manufacture parts and components using these materials. Most 3D printing technologies favour polymers (particularly thermoplastics) as the feedstock for the manufacture of parts. This is mostly due to the ease of producing and handling these materials. The most common polymeric materials used in the manufacture of parts from CAD models using 3D printing include.

4.2.1 Acrylonitrile Butadiene Styrene

Acrylonitrile butadiene styrene is a tough nontoxic polymer utilized in the manufacture of various parts using 3D printing technologies. This thermoplastic polymer is preferred due to its high strength, high water and chemical resistance and low melting point. Limitations of this polymer include unpleasant fumes produced during heating, increased brittleness and loss of colour when exposed to ultraviolet rays. Applications include toys, computer keyboards, and conceptual and functional models.

4.2.2 Polylactic Acid

Polylactic asid is an environmentally friendly plastic polymer made from biodegradable materials such as corn starch, sugar cane, maize and cassava [90]. This thermoplastic according to Balla et al., utilizes 65% less energy and generates 68% fewer greenhouse gases during its production compared to regular polymers [91]. In addition to its eco-friendly properties, PLA is relatively a cheaper option compared to ABS and as such is the preferred option for low-cost 3D printers. Notwithstanding these highlighted advantages, PLA is not as heat resistant as ABS and as such tends to deform at temperatures greater than or equal to 60 °C. It is applied in the medical industry for drug delivery and the production of prosthetics while in the food industry, it is used to make food containers.

4.2.3 Polycarbonate

This is a thermoplastic favoured for the 3D printing of certain products for its lightweight, heat resistance, high strength and toughness. The polycarbonate filament can withstand temperatures ranging from -15 °C to 140 °C making it viable for a wide range of applications including high temperature applications. The hygroscopic nature of polycarbonate is a major issue which allows for high moisture absorption in moist/humid environments. This property is responsible for the production of defective parts.

4.2.4 Nylon

Nylon is a thermoplastic from the polyamides group. Known for its versatility, nylon has been used in several industries such as fashion, electronics, manufacturing, automotive and food industries. Nylon is being used to manufacture parts using 3D printing primarily due to its strength, toughness, flexibility and abrasive wear resistance. Like polycarbonates, nylon is a hygroscopic material and as such, improper storage might lead to the production of defective parts and other related print issues.

4.2.5 Polyethylene Terephthalate

Polyethylene terephthalate is a durable, recyclable and tough material that is used in food packaging and cosmetics. A modified variant of PET is PETG. The ‘G’ glycol modification is applied to PET to reduce its brittleness and improve its overall utilization while manufacturing a part [92]. In addition to its strength which has enabled its application for industrial strapping, ropes and automotive parts, PET and its glycol variant have been successfully applied in the electronics industry due to its thermal and electrical resistance. According to Robertson, PET has been applied as food packaging because of its tensile strength, excellent chemical resistance, and wide operating temperature range (-60 °C to 220 °C) [93].

4.2.6 Polyvinyl Alcohol

Polyvinyl alcohol is a sacrificial material used to produce 3D parts for various applications most notably in biomedicine [94]. Its sacrificial nature is borne out of its ability to dissolve in water. The biodegradability of polyvinyl alcohol makes it an ideal support structure material in 3D printing. Other materials that are currently being used in the 3D printing of parts and components include high-impact polystyrene, composites, thermoplastic polyurethane, resins, metals such as aluminium, steel, titanium, bronze and gold, composites such as carbon fibre, and Nitinol.

5. SUSTAINABILITY IN 3D PRINTING

3D printing technologies have demonstrated over time the potential to replace traditional manufacturing processes. Reasons such as rapid prototyping, the high synergy between design and manufacturing, ease of access and cost-effectiveness are highlighted reasons for the earlier statement. A major indicator that has informed the decisions for most manufacturers to resort to 3D printing as a favoured alternative is the issue of environmental sustainability. In comparison to machining, the utilization of 3D printing produces parts and components with lower environmental impacts per part [95]. Due to the deposition of feedstock stock layer by layer based on the input post-processed CAD design, 3D printing technologies minimize waste and by extension reduce the process and logistics carbon footprint. The absence of specialised tooling has driven down the cost of production using 3D printing technologies hence the switch from traditional manufacturing methods such as machining and injection moulding to additive manufacturing. According to Machado et al., the sustainability advantages of 3D printing compared to other manufacturing methods cut across the design, production, use and disposal of the manufactured components [96]. Other key merits of 3D printing relevant to maintaining sustainability in manufacturing include its ability to build functional lightweight parts, fewer feedstock requirements, decreased carbon footprints, and lower embodied energy [97]. Additionally, Kellens et al. have attributed the ability of 3D printing technologies to produce lightweight components, and supply chain management as potential life cycle benefits compared to other manufacturing processes [98]. Important aspects of sustainability considerations in the utilization of 3D printing technologies for the manufacture of products are material selection and lifecycle analysis.

5.1 Material Selection

One of the major merits of 3D printing is the use of a host of feedstock materials. Major research has shifted towards the exploration of more environmentally friendly alternative feedstock that can be used to produce geometries. To address the issues of material selection as it aligns with sustainable manufacturing of parts and in some case assemblies during 3D printing, Eva Sanchez-Rexach et al. [99] has stated that sustainable resins, filaments and printing inks should be explored to reduce the environmental impact of the 3D manufacturing process. The authors further argued that polymer recycling, upcycling and chemical circularity can also be reliable material consideration methods of sustainable 3D printing. The use of most non-biodegradable materials in 3D printing technologies has been attributed to their relatively better mechanical and physical properties. These materials such as ABS, PC and PET have little environmental benefits owing to their limited recyclability and non-biodegradability. These issues have invoked the need among manufacturers and researchers alike to identify sustainable alternatives to mitigate the ever-growing environmental concerns. As most thermoplastics used in 3D printing as recyclable, which contributes to decreased costs and carbon footprints, mechanical recycling remains the simplest method where the end-of-life part is shredded and reprocessed into the required feedstock.

Although this is the case, recycling of these thermoplastic feedstock has inherent issues particularly the degradation of the feedstock’s properties which each recycling run [100]. To mitigate this, chemical recycling also called feedstock recycling can be considered. Among the methods of feedstock recycling, neutral hydrolysis is preferred due to its environmental cost-effectiveness [101]. In addition to recycling thermoplastics, the use of biodegradable and biomaterials has been explored as a means of promoting sustainability in 3D printing. Biomaterials have been considered as a potential replacement for existing nonbiodegradable materials owing to their environmental suitability. The trade-off however exists due to the reduced mechanical properties such as stiffness, and tensile strength among others. These reduced properties make them unsuitable for high-strength applications [102]. Biomaterials commonly used in 3D printing are categorised into polymers, ceramics and metals [103]. The categorization of biomaterials used in 3D printing is depicted in Figure 12. Biomaterials that are used as feedstock materials have found numerous applications in the healthcare industry majorly as modes of drug delivery, in regenerative medicine and functional organ replacement [104]. The main consumer of biopolymers is the packaging industry where certain biomaterials are used in the manufacture of PET bottles, PLA-based bags and PLA containers [102].

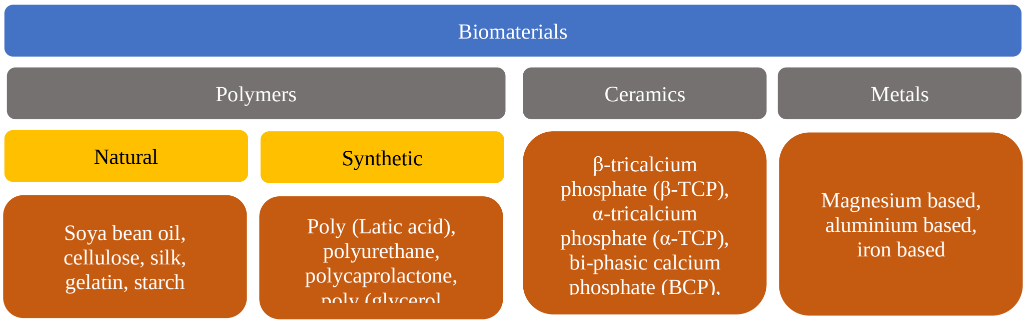

Figure 12. Categories of biomaterials used in 3D printing [99, 102, 105, 106]

5.2 Lifecycle Assessment

Lifecycle assessment is a method that is used to evaluate the environmental impact of a product throughout its life cycle [107]. In the case of 3D printing as well as every other manufacturing process, lifecycle assessment encompasses all stages along the lifecycle of the process. Traditionally, the lifecycle of a typical manufacturing process involves all the stages from the extraction of the raw materials to the disposal of the product after its useful life has been expended (cradle-to-grave approach). Sustainable 3D printing technologies attempt to utilize cradle-to-cradle approaches in the lifecycle of produced parts and components. The cradle-to-cradle approach involves the utilization of recycling technologies as already outlined in the proceeding sections of this work. Cerdas et al have identified 3D printing as a distributed manufacturing system that possesses advantages such as pollution reduction, simplification of the supply chain, and customer freedom [108]. According to Ford and Despeisse, 3D printing technologies are high contributors to the sustainable development of products through the simplification of value chains, improvement of the product lifecycle through stronger person-product relationships and provision of opportunities to improve the efficiency of available resources [109]. Work done by Saade et al. [110] suggests that although 3D printing technologies are very attractive manufacturing forms, lifecycle assessment has pointed out that there exists a need for higher energy efficiency in production processes. In the 3D printing technologies, several sustainable models have been incorporated to ensure low environmental impact. Of such models, cradle-to-cradle and circular economy have been highly favoured as evidenced by several lifecycle assessment attempts. These technologies have been adopted in 3D printing processes to create value at all levels of the production value chain and reduce the effect of the degradation of natural resources [111]. In addition to these models, the biosphere rule has been adopted in certain 3D printing processes as a model that attempts to mimic nature's fundamental sustainability. It has been noted that 3D printing is uniquely suited to implementing the biosphere rules because it emulates the way nature builds organisms. This in addition to the possibility of recycling the feedstock not only decreases the operational energy requirements of the process but also decreases its embodied energy which further decreases the environmental impact of the technology.

6. CONCLUSIONS

This body of work has attempted to explore the importance of 3D printing in the promotion of sustainability in producing valuable items. The reviewed articles have gone to show the existential issues especially the generation and disposal of e-waste. Government legislature and models such as the circular economy, biosphere rules, sustainability pillars and cradle-to-cradle have been created to generate avenues for the enhancement of sustainability efforts throughout the lifecycle of electronic products. The reviewed works have also indicated that the production of e-waste is a worldwide problem which has led to worthwhile attempts by world governments to explore innovative solutions. Efforts such as incentivization, training and retraining of stakeholders, and the development of useful production methods have been applied towards the sustainable production of items. The advent of 3D printing technologies has become a viable method that offers the prospect of creating products by maximizing their social, economic and environmental impacts. Further improvements in the sustainable production of parts using 3D printing include the use of biodegradable feedstock and recycling of feedstock particularly thermoplastics and metals like aluminium. In addition to feedstock reuse and recycling, 3D printers can be reconstructed using e-waste which not only provides an avenue for the promotion of environmental saving but also reduction in associated capital costs.

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