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Review

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Review

Sustainable Additive Manufacturing and Environmental Implications: Literature Review

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Abstract: This study's objective is to review the literature on the environmental impact of the additive manufacturing process. When this new manufacturing technology is employed, it aims to create a healthy environment free of pollutants. The work is motivated by the lack of universal guidelines on new design approaches, the classification of manufacturing materials, and processes that address environmental concerns. Using additive manufacturing over traditional subtractive technologies may result in considerable material and energy resource savings, especially if the component is appropriately designed for manufacture. In this scenario, additive manufacturing, regarded as a potential breakthrough innovation, has grown in popularity in producing parts with complex geometry. AM encourages constant product development and flexible modifications that enable stakeholders to create better products faster. This study examines the state-of-the-art essentials of the fast-expanding manufacturing technique known as additive manufacturing (or 3D printing) and compares the environmental impact caused due to environmental issues. With increasing pressure on firms to provide transparency in their product sourcing and manufacturing processes, sustainability is no longer a distant goal but a strategic requirement. Manufacturers must also pay particular attention to their products' total energy usage and overall environmental impact.

Keywords: additive manufacturing; environmental pollution; sustainable manufacturing; life cycle assessment; energy modeling; energy consumption

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1. Introduction

Additive manufacturing (AM) is a technological advancement that produces three-dimensional objects by layering polymers, ceramics, metals, composite materials, concrete, and human tissue materials in precise geometric shapes. In AM technologies, numerous techniques process liquid, solid, and powder materials, and the forefront processes are illustrated in Figure 1.

In liquid-based AM, vat polymerization is a method of curing liquid photopolymer selectively in a vat using light-activated polymerization [1]. Some of the most common vat polymerization processes are stereolithography apparatus (SLA), which scans and cures the surface of a liquid monomer using an ultraviolet (UV) laser beam to generate a solid polymer [2]. Direct light processing (DLP) uses a digital light projector screen to display a single image of each layer at a time, with each layer composed of square pixels known as voxels [3]. The scan, spin, and selectively photocuring (3SP) process is similar to the SLA process. It moves the laser in the Y direction while scanning in the X direction very quickly and solidifies each layer of photopolymer using the laser's ultraviolet beam [4]. The continuous liquid interface production (CLIP) process is performed by placing an oxygen-permeable window beneath the UV image projection plane, creating a "dead zone" between the window and the polymerizing component [5]. Solid ground curing (SGC) is a photopolymer hardening process that includes completely lighting and hardening the whole surface using specially produced masks [6]. Instead of a laser, daylight polymer printing (DPP) by photocentricity, which uses a liquid crystal display (LCD), is used to cure the polymer [7]. Plastic filament is extruded through a nozzle and deposited layer by layer along a predetermined automated path known as fused deposition modeling (FDM), also called fused filament fabrication (FFF) [8]. Multi-jet modeling (MJM) mixes ultra-thin layers of photopolymer materials with several jets layered on one another on a construction platform and cures with UV light [9].

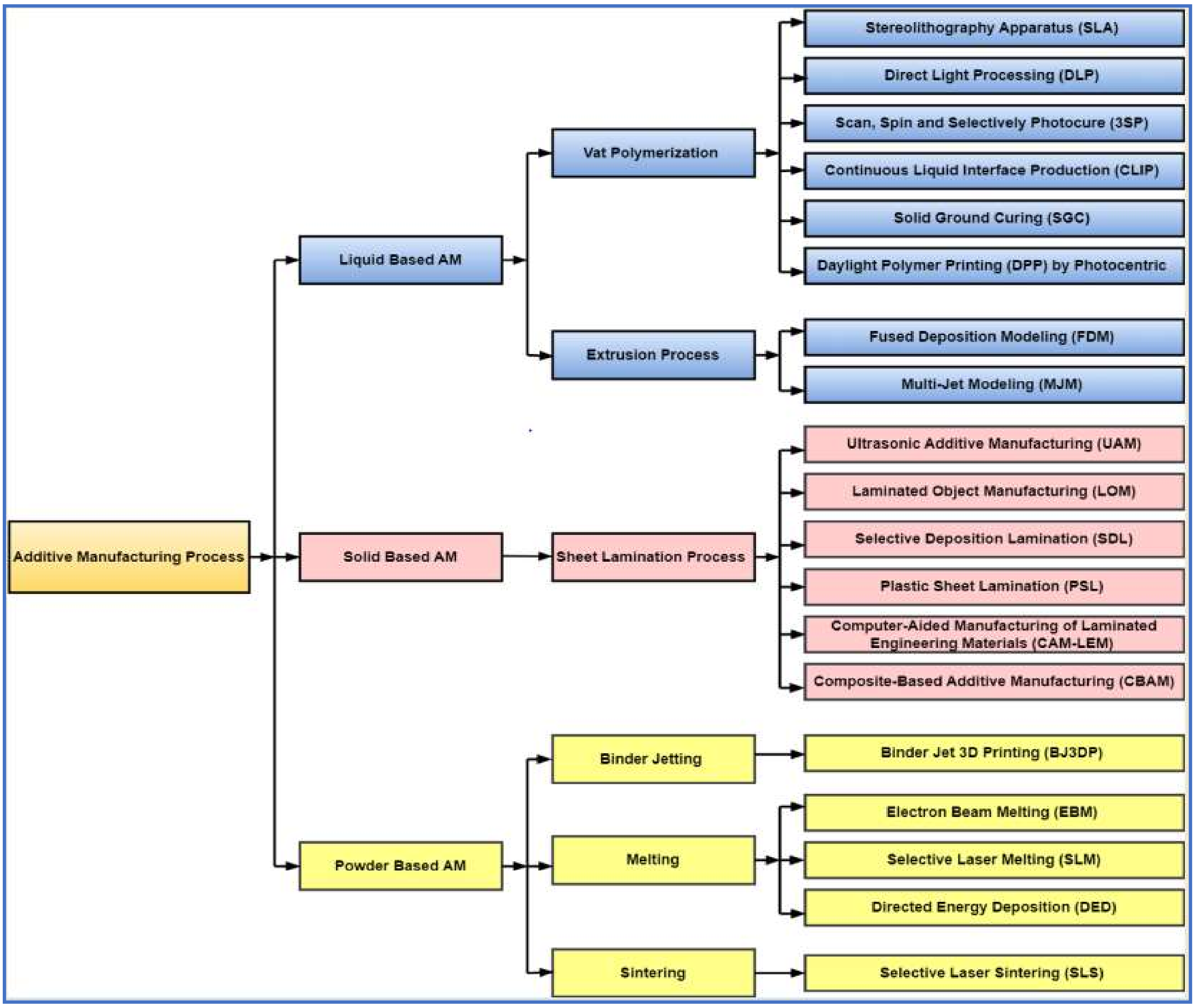

Figure 1. Additive manufacturing processes classification and types.

In solid-based AM, sheet lamination is a process in which thin sheets of polymer materials are bonded together layer-by-layer to form a 3D single object. The sheet lamination is categorized into an ultrasonic additive manufacturing (UAM) process that builds metal workpieces by fusing and stacking metal strips [10]. Laminated object manufacturing (LOM) employs adhesive-coated paper, plastic, or metal that are glued together layer-by-layer to form 3D laminates [11]. The selective deposition lamination (SDL) process is similar to the LOM method but uses paper as the input medium. Selective lamination composite object manufacturing (SLCOM) prints thin laminated thermoplastic composite layer-by-layer to create woven fiber fabric [12]. Plastic sheet lamination (PSL) is a lamination method that employs plastics and polymers [13]. Computer-aided manufacturing of laminated engineering materials (CAM-LEM) is a technology that allows for the direct fabrication of geometrically complicated forms using green ceramic tape and other engineering materials [14]. Sheets of fiber-reinforcing material, such as carbon fiber, are passed under an inkjet printer, which deposits a liquid solution onto the sheet in the form of a layer in composite-based additive manufacturing (CBAM) [15].

In powder-based AM, 3DP binder jetting, also called binder jet 3D printing (BJ3DP), is a method of 3D printing in which a liquid binder is jetted over layers of powdered materials to create solid and complex parts [16]. Electron beam melting (EBM) is a 3D-printing technique that uses a high-energy electron beam to melt a powdered metal, resulting in less residual stress and less deformation [17]. Selective laser melting (SLM), also known as laser powder bed fusion (LPBF), direct metal laser melting (DMLM), or powder bed fusion (PBF), is a process of fusing powdered materials by heating them to melting temperatures [18]. Directed energy deposition (DED) is a method that allows for the production of components by melting the powder material as it is deposited [19]. Selective laser sintering (SLS), also called direct metal laser sintering (DMLS), is another well-known process that utilizes a high-powered laser to fuse powdered industrial materials automatically [20]. The sintering step refers to the selective laser beam scanning of the deposited powder layer, which sinters the powder locally according to the predetermined part slice geometry.

Due to the merits and demerits of AM technology, researchers worldwide have explored a combined additive and subtractive manufacturing technique [21]. An additive machine is a clear-up scaling approach that immediately boosts production capacity, allowing relatively low-capacity processes to reach significant production quantities [22]. Additive fabrication enables designers practically infinite creative flexibility and allows for the mass personalization of consumer products. This process is already employed in high-value medical devices such as hearing aids and medical implants and in the aviation, automotive, and marine sectors [23].

AM has the advantage of building parts having complex shapes from digital design data utilizing materials without waste. As a result, AM technology is considered to have a significant contribution to sustainable, economical, social, and environmental conditions for the manufacturing industry. This review addresses various issues in the ecological spheres of AM technology in terms of environmental-based manufacturing, life cycle assessment, modeling, energy consumption, and sustainable design. As illustrated in Figure 2, this study examines the environmental performance of AM processes.

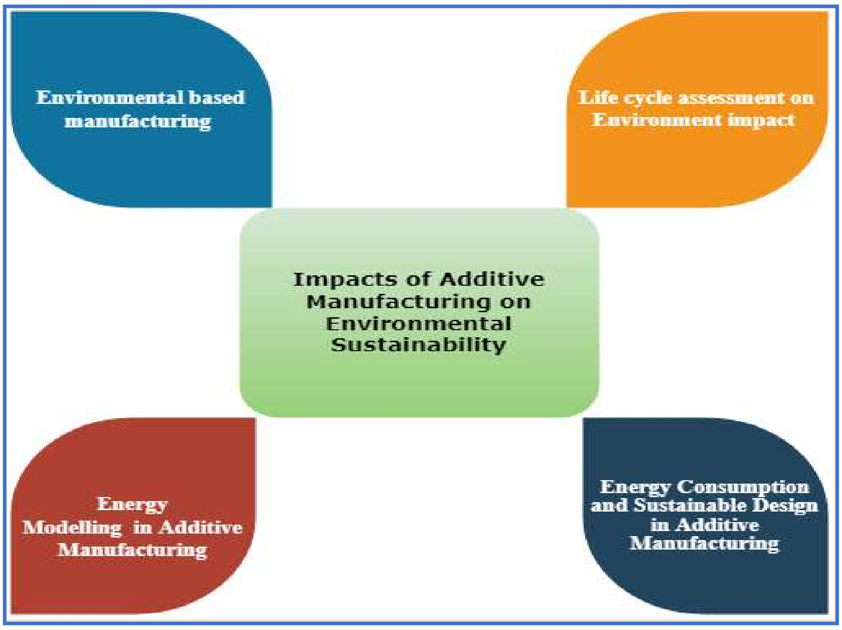

Figure 2. Impacts of AM on environmental sustainability.

2. Materials and Methods

To conduct this study, diverse published papers on this subject were reviewed. As shown in Figure 3, a total of 135 research works published on environmental-based manufacturing were assessed. From the searched and identified publications on the subject, Elsevier publications contribute 56 journals (41%), and Springer publications contribute 21 journals (15.5%).

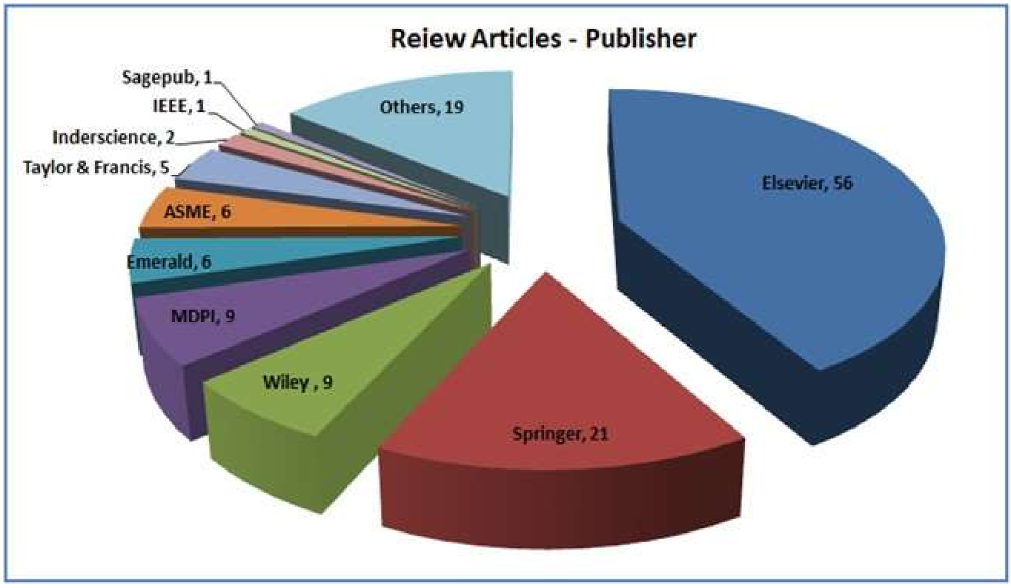

Figure 3. Environmental-based publications on additive manufacturing.

Journal of Cleaner Production, Procedia Journals from Elsevier publications, *The International Journal of Advanced Manufacturing Technology* from Springer publications, *Journal of Industrial Ecology* from Wiley publications, *Materials* from MDPI, and *Rapid Prototyping Journal* from Emerald Publishing have contributed the most to this topic. Figure 3 depicts the environmental publications on additive manufacturing that contribute to ecological sustainability. The researchers in [24] described the process flow of AM stages to enrich ecological sustainability, as illustrated in Figure 4.

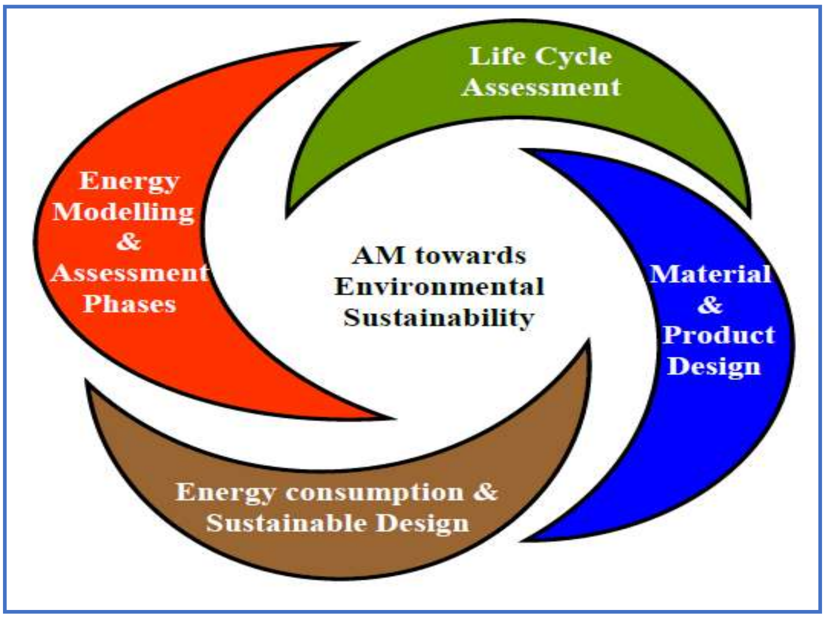

Figure 4. Process flow of AM towards environmental sustainability.

3. State-of-The-Art Study of Environmental Concepts in Additive Manufacturing

3.1. Impacts of Additive Manufacturing on Environmental-Based Manufacturing

Due to the apparent need for substantial changes based on environmental concerns, the manufacturing industry faces economic and technological hurdles due to the use of finite materials and energy resources. The authors in [25] considered that the direct metal deposition (DMD)-based AM technique might be viewed as more environmentally benign than conventional tooling manufacturing. The authors examined three case studies: (1) a simple injection mold insert, (2) an outer-space mirror fixture, and (3) an automobile stamping die. The authors in [26] compared minimizing manufacturing costs by investigating application models for core structures other than cross and honeycomb structures, resulting in opportunities to reduce material usage and production time. The researchers in [27] developed two unique approaches for components and assemblies, A-DfAM and C-DfAM. These AM methodologies help the designers to improve the design topographies.

The authors in [28,29] provided an AM design of product qualities based on environmental data. This method focused on the product development process's early design stages (EDS) to reduce the cost of manufacturing, quality improvement, and opportunity development for a new business. The authors in [30] reported a review to raise awareness of unsolved issues in estimating the environmental consequences of rapid prototyping (RP) and rapid tooling (RT) to identify the actual toxicological health and environmental risk that can arise during the handling, as well as use and disposal of RP and RT materials. This paper presents a method for creating and organizing the information, as well as the study of successful products and designs to reduce the environmental effect of their services with the aid of design for environment (DfE) technologies to assist designers in determining how to overcome this contradiction at the conceptual design phase [31]. The researchers in [32] examined research initiatives to improve the sustainability of nonprocessed aluminum (Al) and iron oxide (Fe_2O_3) lightweight raw materials to be recycled and reused using AM technology, significantly reducing raw material waste. As a result, the nonprocessed raw materials may be recycled and reused by AM to minimize material waste substantially. The authors in [33] presented a design for additive manufacturing (DfAM) by considering design requirements and manufacturing constraints to produce an appropriate design of components manufactured using additive manufacturing.

Furthermore, some guidelines were provided for designing a product using additive manufacturing. The researchers in [34] proposed a method of enhancing AM production strategy in terms of production volume, cost, and the characteristics that impact the application of AM method in medium and high production volumes. The researchers in [35] predicted the future of AM with the perspective of three key elements: (1) applications, (2) materials, and (3) design. In addition, they compared AM technologies with traditional manufacturing methods based on formative and subtractive processes. The authors in [36] investigated the assessment of surface roughness on plane sides of cubic test specimens using layered additive printing technology.

The researchers in [37] proposed a predictive model based on manufacturing and computer-aided design (CAD) model of fluid material and electrical consumption fluxes combined with a global perspective in a sustainable approach with an accurate assessment of flow consumption in the machine. The researchers in [38] examined the societal implications on healthcare products to improve their quality, reduce environmental impact on manufacturing sustainability and increase the efficiency of AM process from a technological standpoint. However, boosting machine utilization over machine and tool allocation is critical to lowering the environmental effect of AM. The authors in [39] proposed a decision-making framework for selecting a compelling portfolio of manufacturing techniques, which included AM and traditional manufacturing technologies using a methodological framework combined with multi-criteria decision aid (MCDA) and data envelopment analysis (DEA). A criticality analysis was performed by [40] using AM strategy to determine the overall production efficiency of the workpieces. The authors in [41] explored a new system based on less energy consumption and resources by considering the economic models of mineral supply chains and 3D production systems to enhance sustainability and lower environmental impacts. A new method was proposed to evaluate the ecological effect of industrial operations. All fluxes consumed and generated (material, fluids, power) are addressed in this technique [42]. The researchers in [43] proposed a framework for the characterization of sustainability as a tool for the community to benchmark AM procedures.

The authors in [44] reported a study on an integrated assessment of the literature on the environmental sustainability of dispersed production in several disciplinary sources. The study highlighted that distributed production provides a different approach to mass manufacturing and the consumer-producer relationship. The researchers in [45] addressed the potential impact of rapid prototyping systems on operator health, safety, and the environment, leading to increased technology adoption in business and academia. The authors in [46] offered an in-depth case study of energy consumption and explained the disparities between direct digital manufacturing and mass production, and highlighted the significant influence on sustainable development. Nevertheless, their study indicated that numerous technical and societal challenges exist to solve. In the SLS process, genetic programming, support vector regression, and artificial neural networks were used to develop laser power-based-open porosity models to improve environmental performance [47]. The authors found that GP is the best model to predict open porosity based on supplied laser power values accurately. The researchers in [48] reviewed and summarized the benefits, drawbacks, and effects of AM on sustainable development concerning innovation sources, business models, and value chain architecture and shed light on the impact of AM on sustainable development. Direct energy deposition as AM and subtractive (milling) process was reported [49] in which different sustainability criteria for components of varying sizes were compared. The material removal rate (MRR) results emphasized that the DED process performs better than sustainable manufacturing.

A method based on the DfAM was proposed in [28] and absorbed into the EDS of the product development process. The aim of the design technology was to facilitate the methodological implementation of environmental decisions. The research reported in [50] demonstrated the use of additive manufacturing technology and traditional thermal imaging techniques to redesign and validate the optimized system's precision to avoid instrumental methodological flaws. The authors explained the differences between experimental and actual values of the aforementioned ecological factors. Desktop-scale FDM machines [51] that can provide insight into volatile organic compounds (VOC) emissions from industrial-scale material extrusion machine printing were investigated using ABS and PC filaments. The researchers in [52] presented an overview of life cycle inventory data by comparing the environmental impact of different additive manufacturing processes, including selective laser melting, selective laser sintering, electron beam melting, fused deposition modeling, and stereolithography, in which the ecological evaluation considered energy usage.

Reusing materials reduces the environmental burden by lowering the amount of fresh material needed. As reported in [53], specific components may be created with a low ecological load using additive manufacturing for customization. A process planning design strategy was also developed [54] focusing on material usage in additive manufacturing. Tests were performed using the sustainable manufacturing method, and the results showed that the effectiveness and feasibility could be increased by reducing material consumption. The authors in [55] provided a life cycle evaluation technique that compared the environmental consequences of several impeller production technologies, such as plunge milling, laser cladding forming, and additive remanufacturing (RM). The authors in [56] focused on technical factors to highlight the features and effectiveness limits of the FDM technique of plastic components production capacity and also considered the economic aspects to analyze the expenses associated with the various procedures. The usage of a stainless steel (SS) micro powder and a cement paste combination in AM was also reported in [57]. The optimum quality, strength, and durability were achieved by adding 5% SS micro powder to the cement paste. The researchers in [58] investigated the recycled SS 316L powder using X-ray photoemission spectroscopy (XPS), scanning electron microscopy (SEM), X-ray Diffraction (XRD), and rheology analysis. Reusing the recycled powders during the AM process considerably decreased powder consumption, production cost, and time. This work aimed to measure the performance parameters of WAAM-based processes and offer a multi-criteria decision-analysis mapping to assess the combined effects of items produced using the WAAM-based technique and machining [59]. The literature results demonstrated and analyzed the overview and impacts of AM in environmental-based manufacturing.

3.2. Life Cycle Assessment on Environment Impact

Life cycle assessment (LCA) is the most often utilized technique throughout the design process, and analysis of the environmental impact of input and output flows in production processes that may be attributed to the stages of a product's life cycle. For instance, according to the LCA, powder elaboration and ingot manufacturing account for approximately 90% of the environmental consequences in machining. The study reported in [60] aimed to examine all critical sources of environmental impacts, including energy usage, waste, and tool production, as well as all major categories of impacts. Further research aimed to recommend that manufacturers produce the components utilizing AM, which are free from environmental effects, such as climate change, land usage, and toxicity, was reported in [61].

Design flexibility allows product parameters such as weight and effectiveness to obtain a superior life cycle performance [62]. Though size limitation is one of the key constraints, the potential of 3D printing technology for the construction sector is considered based on the findings gained from each work phase, particularly the case studies analysis [63]. The authors declared that the goal of many manufacturers and academics was the long-term viability of the built environment in terms of economic, environmental, and social advantages. The environmental performance of a revolutionary additive manufacturing technique, known as rapid mask-image-projection-based stereolithography, was assessed using a life cycle evaluation to find damage to ecosystems and human health [64]. The study was conducted in different approaches to decrease economic risks, carbon and ecological footprints, and environmental impacts of 3D printing technology to minimize the environmental impacts and costs associated with traditional manufacturing methods [65].

The impact of the LCA of AM process is significant in applying the technology in remanufacturing, reconstruction, and repair areas. The experimental result reported in [66] focused on the difference between semi-automated geometrical reconstruction and laser direct deposition methods to effectively repair faulty voids in turbine airfoils, which showed that direct laser deposition is successful in remanufacturing and can respond to a wide range of part faults. In the binder-jetting process, a generic framework was developed to incorporate the design stage in LCA to reduce the environmental effects of AM processes [67].

The research reported in [68] recommended an LCA approach and associated decision criteria to assist the choice of a manufacturing method for an aeronautical turbine. The dimensionless measures used enabled environmental trade-offs between subtractive and additive approaches. This study calculated the net changes in lifecycle primary energy use and greenhouse gas emission with AM for lightweight metallic airplane components to shedding light on the unique benefits of switching from conventional manufacturing (CM) to AM procedures [69]. To assist eco-design activities in the aeronautics sector, an eco-efficiency technique integrating life cycle costs and life cycle environmental evaluation was developed that accounts for particular reduction objectives such as equipment costs, materials costs, and environmental impacts [70]. The authors in [71] conducted a case study using a train's binder jetting AM process with a modified floor connection.

AM technique is used as the standard manufacturing process to find the lack of end-of-life data and a modest influence on maintenance and fuel efficiency and examine the impact on the environment on output. As demonstrated in [28], to improve the design features of DfAM, the research must focus on the early design stages to reduce environmental impacts. The authors in [72] created a methodology to supplement the LCA of an AM material to minimize hazards, human health, and ecological implications. A feasibility study was carried out by [73] to evaluate the applicability, manufacturing time, and production costs of AM versus CM of specified metallic construction components. Second, the authors' analysis of LCA examined the environmental implications of AM and CM. The researchers in [74] compared conventional manufacturing processes with AM, exposed the AM system emissions, the impact of raw materials utilization, and operating parameters, and developed suitable control measures and best practices for hazard reduction. Four LCAs were also conducted [75] for mold core production techniques, including casting with low-melting alloy, milling from plaster-like substance Aqua pour, additive manufacturing with high-impact polystyrene (HIPS), and additive manufacturing using powder materials such as salt. The study also analyzed the environmental consequences of traditional and additive mold core manufacture in CFRP production.

The researchers in [76] used life cycle inventory (LCI) and LCA data demonstrating that AM can be a good alternative for making bespoke parts or short production runs as well as complicated part designs, generating significant functional advantages throughout the part-use phase. This research focused on environmental evaluation and a methodology based on the LCA technique presented by [77]. This suggested technique can assist designers and manufacturers in selecting the best strategy for producing new components from existing parts while minimizing the environmental effect. An updated LCA methodology and a software concept were also established in [78] to quantify the environmental implications of using AM technology.

The experiments performed and reported in [79] to calculate the total process and coating performance aimed at better understanding the coating process's underlying mechanisms and the influence of operational factors. As part of the study, an LCA was conducted to validate the suggested technology's efficacy in environmental issues, energy consumption, and cost. The investigation compared two different life cycles of two comparable insoles: one manufactured using traditional manufacturing and the other produced using 3D-printing technology. These were examined using the same scale production to find how environmental consequences can be addressed in this paradigm of AM utilization vs. traditional manufacturing [80]. The environmental impact of direct metal laser sintering of iron metal powder and fused deposition modeling of acrylonitrile styrene acrylate polymer filament were investigated in this work. The study showed that electrical energy usage is the primary contributor to the systemic environmental implications of additive manufacturing [81].

The researchers in [82] measured the inventory data of AM processes during a product's lifecycle production stage. This work also explained the creation of a parametric process model that provides an operator with reliable estimates of the environmental performance of the fused deposition modeling process. The authors in [83] conducted LCA research, which aimed to contribute beneficially to making decisions for polymerizable ionic liquids (PIL) 3D-printing methods at the laboratory scale. The findings of this study aided in identifying the significant elements and environmental implications associated with the creation of monomer ionic liquids (ILs) and PILs additive manufacturing. A novel approach for assessing environmental effects and a technological and financial assessment was proposed in [84] and applied to several additive manufacturing methods, which can assist firms in making a multi-criteria production process selection.

Energy consumption in AM is one of the areas that deserve research. The researchers in [85] investigated common AM processes' specific energy consumption (SEC) and environmental consequences. The prospects of ensuring product quality while reducing energy usage were investigated using experimental analysis. The investigation was carried out to study the environmental effect of WAAM using LCA. Due to the high impact of stainless steel, this evaluation incorporated significant sources of uncertainty and is sensitive to variations in material use fractions [86]. This research aimed to provide an overview of the literature on the environmental performance of AM and to examine the application of LCA [87]. The authors in [88] studied the possible environmental consequences of AM in terms of essential concerns such as energy usage, occupational health, waste, lifecycle effect, and cross-cutting and policy issues as current research requirements and suggestions. The environmental impact in this article was based on LCI data such as energy, material, and fluid. Predictive models of environmental effects must be developed to ensure the continued development of the processes so that goods may be assessed not only from a technical and commercial standpoint but also from an environmental standpoint [89]. The study was conducted with an emergy-based lifecycle assessment (Em-LCA) technique which was used to compare the sustainability of laser-engineered net shaping (LENS) machining against that of CNC machining for gear production [90].

An LCA-based study was also conducted [91] using powder bed fusion (PBF) of metal components of an engine in a light distribution truck. Conventional manufacturing was contrasted with 3D-printing scenarios, one indicating the current stage of development of 3D-printing technology and the other a probable future state. The authors in [92] researched the evaluation of new materials for paste extrusion printing. LCA technique was used to compare their whole-system environmental implications to typical ABS extrusion: testing also evaluated material strength, printability, and cost. The reported research on AM's environmental impact emphasizes gaps and places where more study is needed. Finally, the effects of reusing metallic powder and the waste disposal processes were investigated [93].

The LCA for an inkjet fusion printer with unusually high spatial utilization capability was performed in [94], which compared with earlier LCAs of nine printers produced with eight materials. However, when evaluated in the same usage situations, the inkjet fusion printer had a more significant environmental effect per component than other printers due to its high energy consumption.

The investigation was carried out, and a comparison of AM data from the literature on lifecycle evaluation was made with traditional industrialized data from the Granta EduPack database. According to the authors [95], the AM had considerably larger CO_2 footprints per kilogram of material produced than casting, extrusion, rolling, forging, and wire drawing. When this pertains to the manufacture of medical implants, this study analyzed whether AM is more environmentally friendly than CM. The environmental impact of producing the femoral component of a Ti-6Al-4V knee implant was examined. For the fabrication of this component, one AM process, i.e., EBM and milling operation, were investigated [96]. The authors in [97] undertook a life cycle environmental comparison of two different versions of a product fabricated utilizing additive technology. The products' structures were the same, and the study trials involved modifying the materials used in additive manufacturing (from PLA to ABS). The impacts of adjustments on environmental factors were noted, and a direct comparison of the effects in the various components was performed. The life cycle assessment is accomplished in the brick-making process to assess environmental impacts considering conventional production systems and olive mill wastewater [98].

Overall, it is vital to assess the actual environmental impact of new manufacturing methods. The LCA, among other things, facilitates opportunities to build sustainable products and processes, provides information to decision-makers in businesses and government organizations, selects environmental performance indicators, and assists with green manufacturing and marketing.

3.3. Energy Modeling in Additive Manufacturing

Energy models in additive manufacturing allow determining which aspects of the machine contribute the most to global environmental effects to reduce energy consumption. The modeling approach involves simulating each machine characteristic that influences the environment.

A novel approach was proposed to assess the environmental effect of all flows (materials, fluids, and power). The conventional approach is based on a predictive model of flow consumption specified by the production process and a CAD model of the item to be produced [37]. A novel technique for assessing electric, fluid, and raw material consumption in AM processes can be done by direct metal deposition. The method assists engineers in designing environmentally friendly products for additive manufacturing [99]. An experimental design is utilized to investigate the impact of production volume, material and operational costs, batch size, material machinability, and lowering AM processing time. The generated models give insight into how these variables impact the expenses of creating a mechanical product manufactured using AM and SM technologies [100]. In a study reported in [101], a CAD model of a product was created, and the manufacturing program was utilized to create a prediction model of flow usage that aims to reduce production environmental effects during the design stage. A study on empirical research was conducted [102] by presenting an optimization framework for estimating laser energy consumption in the SLS process. This study's experimental approach included the calculation of energy consumption by measuring the whole sintering area. A comparison of a machining strategy with an integrated production path based on an AM process plus finish machining was reported in [103], whose primary outcome was a criterion for selecting the best environmentally friendly manufacturing technique while modifying the production scenario. An energy modeling for FDM printing was also developed [104] to investigate from a life cycle viewpoint. The steps covered in a typical FDM life cycle included material manufacturing, printing, post-processing, and associated transportation. This model uses energy for each stage and measures unit energy consumption. Thus, the objectives of the study were to create a conceptual model for manufacturing to redesign products, identify AM process adoption possibilities, and apply the AM process in production [105]. The researchers in [106] studied and compared several environmental production processes for components composed of aluminum alloys. Life cycle assessment methodologies were used to study and compare SLS-based AM processes, machining, and shaping operations.

3.4. Energy Consumption and Sustainable Design for AM

The utilization of resources without exhaustion or negative environmental impact is called sustainability. Significant sustainability challenges in manufacturing include energy use, waste creation, water usage, and the manufactured item's environmental effect. Sustainability concerns global ecological conditions (environment), economic development (technology), and societal equality. Engineering procedures are typically associated with economic progress.

To minimize the amount of energy used in SLS of non-polymeric materials, work was reported in [107]. The strategy of this work was to mix a temporary binder with the material, make an SLS green part convert the binder, and densify the part by chemical deposition at room temperature inside the pore network. The authors in [108] have also compared the electrical consumption of two major polymeric SLS platforms: the 3D Systems Sinterstation HiQHS and the EOSINT P 390 from EOS GmbH. The measured energy rates were more significant than the reported and also demonstrated that the primary energy drain is entirely time-dependent energy usage. A method for developing an energy consumption model for the binder-jetting manufacturing process's printing stage was described in [109]. Mathematical investigations were carried out to determine the relationship between energy usage and the geometry of the produced item. This process model is a tool for optimizing part geometry design regarding energy usage. The study was conducted to improve understanding of the energy inherent in each phase of the manufacturing process. To make the helpful model, users should calculate the energy spent by their manufacturing process equipment based on the energy-per-unit production volume for each material of interest, considering both alloy composition and shape [110].

The researchers in [111] analyzed a range of items and industries in this study to fully grasp the function of additive manufacturing in sustainable industrial systems. Four major areas where the use of additive manufacturing is improving resource efficiency can be identified: (1) products and process design, (2) material input processing, (3) product and component production to order, and (4) completing the loop. The authors in [112] examined AM good's overall life cycle sustainability using the newly developed Product

Sustainability Index (ProdSI) methodology. A case study was conducted with two iterations of an AM product confirming the ProdSI metrics of AM products. Furthermore, the features of additive manufacturing from the standpoint of sustainable design and the possibility of a new business model that might result in the sustainable design of consumer items were reported in [113]. The primary environmental benefits of using AM technologies in industrial production include lower energy consumption of printers throughout the manufacturing process, ease of product decommissioning and disposal, reduced waste, and enhanced raw material recycling rate [114]. The authors in [32] reviewed research initiatives that were carried out at the University of Exeter to improve the long-term viability of AM. These research efforts included: (1) sustainable product design through internal lightweight structure optimization, (2) process efficiency improvement through AM process parameter optimization, (3) energy consumption reduction through in situ thermite material reaction, and (4) sustainable production of individualized chocolates. Research on electric energy consumption of various processes was conducted [115], followed by some extensive studies that considered raw materials and all the process processes' flows. The study provided a novel approach for accurately evaluating the environmental effect of a part based on its CAD model. The researchers [116] experimented and identified the machine effects, and aluminum powder impacts were computed using life cycle inventories of materials and processes; electricity usage was monitored using an in-line power meter, and transport and disposal were also evaluated. Energy consumption was used to calculate the impacts. A study was conducted and reported in [117] in which the part was manufactured and studied its construction orientation and interior filling, production time, energy consumption, and the product's end-of-life. The study was further intended to assess the environmental implications of traditional manufacturing processes against AM for a real-world industrial application. The repair procedure of a burner was utilized in Siemens industrial gas turbine, and the results indicated that the AM-based repair procedure significantly reduces material footprint and primary energy use [118].

A mathematical model for energy consumption of SLA-based procedures was also proposed [119], and experiments were conducted to assess the actual energy usage from an SLA-based AM machine. The comparative study results demonstrated that the overall energy consumption of SLA-based AM processes might be significantly lowered to optimize parameter settings without visible product quality degradation. According to [120], who created a system modeling framework using life cycle inventory analysis and results, the AM has the potential to save 3 to 5% primary energy, 4 to 7% GHG emissions, 12 to 60% lead time, and 15 to 35% cost over 1 million injection molding production cycles.

Nagarajan and Haapala [121] conducted a study to uncover the systemic contributions to environmental effects in AM by exergy analysis and life cycle impact assessment. These methodologies were used to assess the environmental performance of conventional and non-conventional manufacturing processes. Yang and Li [122] studied how to enhance the state-of-the-art sustainable environmental assessment for AM batch processes by comparing key environmental sustainability characteristics (i.e., energy consumption, emission, and material waste) with batch production processes of varied batch sizes. This study covers the critical sustainability challenges in AM manufacturing technologies.

Material waste and energy usage are two critical issues of the AM processes that demand prompt attention. The study [123] reported, formulated, and optimized the processes at layer and part levels to make AM more sustainable. The Sustainable Value Road mapping Tool (SVRT) prototype for AM was also presented. The results integrated and expanded on previously highlighted possibilities and difficulties in the literature. Case studies were conducted in organizations implementing AM technology to better appreciate the sustainability benefits from a business standpoint [124]. A strategic sustainability life cycle evaluation in the early development stage tested in [125] intended to clarify the sustainability benefits and limitations of AM technologies utilized in the industry. The results demonstrated the tool's capabilities and areas of particular interest in the AM technologies' potential for advancement. The study attempted to clarify the sustainability benefits and constraints of AM technology used in the industry by testing and using a strategic sustainability life cycle evaluation during the early development stage. The outcome demonstrated the tool's capabilities and areas of particular interest in the AM technologies' potential for advancement [126]. The present state of research on energy consumption at the machine and process stages was summarized in [85], in which machine level energy consumption by AM machine tool subsystems such as high energy beam generators, control systems, and cooling systems are considered. The authors in [127] examined the possible impact of AM on global energy consumption with expanded vs. constrained globalization and limited versus widespread AM implementation. These scenarios were created and tested in two examples, the aerospace and construction industries, to examine the impact of AM on each stage of the value chain.

The researchers in [128] conducted holistic modeling of additive and subtractive techniques that may be used to determine the manufacturing path with the lowest energy consumption or CO_2 emissions. The models account for the critical process factors and the effects of the AM redesign for the production of Ti-6Al-4V components. The research reported [129] examined the impacts of incorporating nano-crystalline powders of iron, silicon, chromium, and aluminum into recycled polypropylene high-density polyethylene plastics feedstock for filament extrusion. Physical and mechanical analytical studies found that adding 1% Fe-Si-Cr or Fe-Si-Al improved thermal stability by up to 37% and 17%. A novel support generation technique that addresses both interior and external support via process planning to minimize overall material consumption, manufacturing time, and energy usage was suggested in [130], and the findings indicated that the suggested method significantly reduces all aspects of making AM a more ecologically friendly and sustainable manufacturing process. The authors in [131] identified and prioritized the factors that influence adoption and defined the role of sustainability advantages in the choice to adopt. The findings reveal that environmental sustainability advantages are scarcely relevant to adoption decisions, despite the literature claiming massive sustainability benefits. AM technology's environmental sustainability and its applications were investigated [24]. The report highlighted twelve practical uses of artificial intelligence for sustainability. The use of organic feedstock with improved recyclability, reuse, or recyclability looks to be the most straightforward path to increase sustainability and lower the carbon footprint of future AM plastic processes [132]. The researchers presented a comprehensive framework for Green chemistry addressing sustainability challenges. This research can assist enterprise management in achieving a cultural and economic shift toward sustainability and the circular economy (CE) [133].

The detailed state-of-the-art review of the concept of sustainability and the environmental impact of the AM process has been presented above by classifying it into four specific areas: (1) the impact of the process on environmental sustainability, (2) the life cycle assessment of the process, (3) energy modeling in AM process, and (4) energy consumption and sustainable design for AM. The key aspects and impacts analyzed in the reviewed articles and their results are summarized in Tables A1–A4, respectively, and can be found in Appendix A.

4. Discussion on Environmental-Based AM

Based on a study of existing research on the environmental consequences of AM, four topics have been highlighted to understand the current review better. Future research prospects and limits are also mentioned.

As discussed earlier, the new manufacturing method using AM is gaining huge interest due to the various challenges in traditional manufacturing, such as being economically expensive, energy-intensive, having a limited volume of production, the type of materials used, manufacturing constraints for complicated designs, the length of time to deliver products to customers, etc. The use of AM manufacturing technologies in industries results in lower energy consumption, ease of product decommissioning, disposal of waste, reduction in waste, and raw material recycling, which can be mentioned as some of the advantages.

Impacts of AM in environmental-based manufacturing: AM technologies are more environmentally friendly than traditional production methods, and it is critical to assess and compare the environmental effect of AM technologies to that of traditional production. Limited research was conducted in the AM processes such as MJF, SLS, and FDM and there is a significant research gap in the application-oriented environmental-based AM processes such as medical design and manufacturing (MD&M), energy dispersive spectroscopy (EDS), and WAAM.

Stainless steel, thermoplastic, aluminum alloy, resins, polymers, titanium alloy, polyamide, and nylon are used in the experimentations. Future research is needed in the different types of alloy materials, combining different metals and alloys in a single product. To reduce the mass of an object, reduce material usage, have high strength, and maintain structural integrity, the use of lattice-based design and topology optimization techniques must be focused more on AM-based production. Topology-optimized design of complex parts can be fully realized when AM approach is utilized.

Life cycle assessment on environment impact: LCA has been a highly appealing way to evaluate the environmental performance of AM. LCA is based on a different database for analyzing the environmental consequences related to the specific process on various assumptions and simplifications. There are relevant data gaps, both upstream and downstream, of LCA, and these factors limit the practical utility of LCA studies for product/process development and policy formulation. However, the provided LCA results were not comparable because of differences in data inventory, LCA techniques, LCA boundaries (cradle to gate, cradle to grave), and study objectives. In this survey, the material used in the LCA approach studies is Ti6Al4V, steel, glass, plastic, epoxy resin, copper, aluminum, cast iron, and stainless steel. In the LCA approach, studies are needed in different alloy materials, polymers, composites, natural rubbers, etc.

Energy modeling in AM: Energy models for various AM technologies reported in the literature were also highly diverse. Models with differing outcomes have distinct foci, approaches, measurements, and boundaries. A careful investigation of these models is necessary to determine the reasons for model deviations.

Energy consumption and sustainable design of AM: Energy usage is investigated only at process and machine levels. The link between energy consumption and the efficiency of the printed object, distribution, and product recycling is not explored. The energy efficiency of product recycling will be discussed. The prospective ways of improving energy conversion efficiency for metal AM, such as product design and production optimization, are to be examined qualitatively and quantitatively.

5. Conclusions

Sustainability addresses our demands without compromising future generations' ability to meet their own. The pillars of sustainability are human, social, economic, and environmental sustainability. This article reviewed the environmental implications of additive manufacturing, from raw material manufacturers to product design, printing, post-processing, and product disposal. This article concerns the impacts of environmental-based AM, life cycle assessment on environmental impact, energy modeling in additive manufacturing, energy consumption, and sustainable design. The newest research development examined environmental consequences on manufacturing, LCA perspectives, energy modeling and sustainability, and energy analysis.

In summary, we may infer that AM has a more significant potential for long-term production than subtractive manufacturing (SM). Energy consumption has been identified as a substantial contribution to the positive environmental effect of AM, although product redesign options appear promising for achieving AM sustainability. This study might help research cope with industry constraints and give research possibilities for sustainability to enhance industry AM adoption. However, a thorough investigation of the sustainability index assessment is required. As a result, AM technology is still in its early stages and requires further research to lower material and machine costs, create quicker and more accurate printing processes, and function autonomously.

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Appendix A

Table A1. Summary of the impact of AM in environmental-based manufacturing.

Sl. No.	Authors	AM Process	Raw Materials	Aspects and Impacts Analyzed and Its Results
1	Morrow et al. (2007) [25]	Metal Deposition-based manufacturing (MDM)	Metal powder	Reduction in manufacturing cost, emissions, and energy consumption
2	Lušić et al. (2015) [26]	Finite element simulation	ABS-M30 Thermoplastic	Minimization of consumption of material
3	Floriane Laverne et al.(2015) [27]	Design for additive manufacturing (A-DFAM)	Case study	To improve their design features
4	Markou et al. (2017) [28]	Early Design Stages (EDS)	Metal (Aluminum alloy)Polymer (ABS extrusion)	Design to environment approach
5	Ponche et al. 2012 [33]	Design For Additive Manufacturing (DFAM)	Stainless steel	Determination of suitable design of parts
6	Campbell et al. (2012) [35]	Objet Polyjet process	SL resins	Predicts the future of additive manufacturing
7	Dezso and Kósa (2012) [36]	OBJET Eden 350V additive machine	Plastics	Surface roughness measurement
8	Bourhis et al. (2013) [37]	Direct additivelaser manufacturing (DALM)	Metallic Aluminum Powder	Minimization of material, fluids, electricity
9	Achillas et al. (2015) [39]	multi-criteria decision aid (MCDA) and data envelopment analysis (DEA)	Polymers, metals, ceramics, and composites	Decision-making methodological framework
10	Garg and Lam (2015) [47]	Selective laser sintering	Hydroxyapatite powder and SLS polymer powder, Polyamide-12	To predict open porosity
11	Francesco Salamone et al. (2017) [50]	Thermographic analysis	Comparison study	To ensure the correctness of the optimized system and avoid systematic instrumental mistakes.
12	Jin et al. (2017) [54]	Skeleton-based path planning method	Material consumption model	To improve the deposition performance and surface quality
13	Peng et al. (2018) [55]	conventional manufacturing (CM), additive manufacturing (AM), and remanufacturing (RM)	Titanium alloy	Comparing the environmental consequences of several impeller manufacturing processes
14	Tagliaferri et al. (2018) [56]	Fused deposition modeling (FDM), multi-jet fusion (MJF), and selective laser sintering (SLS)	Polyamide 12,Nylon 12	Highlight the characteristics and, performance limits, costs associated with the different processes
15	Melugiri-Shankaramurthy et al. (2018) [57]	Recycling of metal powder	Stainless Steel (SS) micro powder	To increase quantity, strength, and durability
16	Gorji et al. (2019) [58]	Selective laser melting process.	Virgin and recycled Stainless Steel	The amount of oxygen on the surface of the recycled powder and metallic oxides is growing
17	Priarone et al. (2020) [59]	Wire Arc Additive Manufacturing (WAAM)	Aluminum frame, Steel beam, Titanium bracket	For comparison, the materials' production time, product cost, and mechanical performance were all taken into account

Table A2. Summary of the life cycle assessment of AM process.

Sl. No.	Authors	AM Process	Raw Materials	Aspects and Impacts Analyzed and Its Results
1	Serres et al. (2011) [60]	Construction Laser Additive Direct Process (CLAD)	Ti6Al4V	To analyze the case of a repaired part
2	Faludi et al. (2015) [61]	ReCiPe Endpoint H methodology in SimaPro software	Steel, glass, and plastic	Lowest effects in both maximum and most minor use of machinery
3	Malshe et al. (2015) [64]	Stereolithography	Epoxy resin (SLA 5170)Epoxy resin (SLA 5171)Epoxy resin (SLA 5172)Epoxy resin (SI 500)	Curing of a single resin type and power usage
4	Wilson et al. (2014) [66]	CAD and geometric reconstruction algorithm	SS316L turbine blade	Effectiveness of direct laser deposition in remanufacturing
5	Tang et al. (2016) [67]	BJAM	Ti-6Al-4V	Binder-jetting AM process energy and material consumption models
6	Huang et al. (2016) [69]	Lifecycle Management	Emissions calculation	Primary energy and greenhouse gas emissions
7	Yang et al. (2017) [71]	Binder jetting additive manufacturing process	Green powder, Bronze powder	Reducing energy consumption and environmental impact
8	Bours et al. (2017) [72]	Photopolymerization processing AM	Polylactic acid, PR48 materials	Minimizing their hazards and environmental impacts
9	Kafara et al. (2017) [75]	High Impact Polystyrene (HIPS)	Plaster-like material Aquapour	Comparing the environmental impact of AM with CM.
10	Paris and Mandil (2017) [77]	Electron beam melting and CNC machining processes	Titanium	The material volume of the existing part reused increases by more than 60%
11	Guarino et al. (2017) [79]	Graphene electrode position.	copper	Thermal tests showed improvements in the thermal performances of the samples
12	Nagarajan and Haapala (2018) [81]	FDM	Acrylonitrile styrene acrylate polymer	Electrical energy
13	Yosofi et al. (2018) [84]	Fused deposition modeling, Material jetting	Material consumption	Electric consumption
14	Liu et al. (2018) [85]	Inkjet Printing Extrusion, SLA FDM, LENS	Inconel 718 powders, Stellite 1 powders, AISI 4140 powders Triboloy T800, Resin, ABS, Cell, Slginate	Energy consumption
15	Bekker and Verlinden (2018) [86].	Wire and Arc Additive Manufacturing	Stainless steel 308l	Product shape, function, materials, and process locales
16	Yosofi et al. (2019) [89]	Material jetting	Material consumption model	AM processes that allow products with complex geometries to be manufactured
17	Jiang et al. (2019) [90]	Laser Engineered Net Shaping (LENS)	AISI 4140	Proposed to improve the sustainability of the manufacturing technologies
18	Böckin and Tillman (2019) [91]	Powder Bed Fusion (PBF)	Aluminum, Cast iron, Low-alloy steel, Stainless steel	Designing components for weight reduction.
19	Faludi et al. (2019) [92]	Compression and tensile tests	ASTM standard D638	Comparison of 3D printers
20	Van Sice and Faludi (2021) [95]	Granta EduPack database	steel, aluminum, and titanium	To build volume, energy efficiency
21	Lyons et al. (2021) [96]	Electron beam melting	Ti-6Al-4V material	Reduction in material using the AM process

Table A3. Summary of energy modelling in AM.

Sl. No.	Authors	AM Process	Raw Materials	Aspects and Impacts Analyzed and Its Results
1	Bourhis et al. (2013) [37]	Direct AdditiveLaser Manufacturing (DLAM) process	Steel	Flow consumption
2	Le Bourhis et al. (2014) [99]	CAD model, MacroCLAD	Metallic, ceramic, glass	Electrical consumption, fluids, and material consumption
3	Manogharan et al. (2016) [100]	CNC-RP and AIMS.	Ti6Al4 V	Effect of the costs in AM and SM methods.
4	Kerbrat et al. (2015) [101]	CAD model,	Material, fluids, electricity	minimize the environmental impacts
5	Panda et al. (2016) [102]	SLS, SLM, and GP	TAS and laser energy	Minimizes the energy consumption
6	Priarone and Ingarao (2017) [103]	Machining, EBM, SLS	Ti-6Al-4V, Stainless steel	Energy demand and CO_2 emissions
7	Peng and Sun (2017) [104]	FDM	poly lactic acid	To assist calculation of a life cycle energy consumption
8	Zhang et al. (2018) [105]	Selective laser sintering	Titanium	Bone structure yields—lowest cost and environmental impact.

Table A4. Summary of energy consumption and sustainable design for AM.

Sl. No.	Authors	AM Process	Raw Materials	Aspects and Impacts Analyzed and Its Results
1	Sreenivasan et al. (2010) [107]	SLS	Polyamide powder	Reduce energy consumption
2	Baumers et al. (2011) [108]	SinterstationHiQ+HS	Nylon 12	Reducing the time-dependent energy consumption
3	Xu et al. (2015) [109]	Binder- Jetting	Stainless steel, ceramic, polymer, and glass	Part geometry design to optimize energy consumption
4	Watson and Taminger (2015) [110]	Laser or electron beam processes	Solid metallic material	Improved knowledge of the energy
5	Hapuwatte et al. (2016) [112]	ProdSI	Cobalt-Chromium alloy, Co-30Cr-5Mo	Sustainable for complex geometrical components
6	Hao et al. (2010) [32]	Selective laser melting	Aluminium, Aluminium + Iron oxide	Identify sustainable engineering materials
7	Faludi et al. (2017) [116]	SLM printing	aluminum powder	Reductions in energy consumption
8	Walachowicz et al. (2017) [118]	LBM process	Nickel-based superalloy	Energy consumption and carbon footprint
9	Yang et al. (2017) [119].	Stereolithography (SLA)	Polymer, Epoxy resin,	Overall energy consumption
10	Nagarajan and Haapala (2017) [121]	Direct metal laser sintering	iron metal powder	Electricity consumption
11	Yang and Li (2017) [122]	SLA process	Liquid Resin	Environmental sustainability
12	Verma and Rai (2017) [123]	Selective laser sintering (SLS)	Un-sintered powder material	Sustainability is formulated and optimized
13	Despeisse et al. (2017) [124]	Sustainable Value Roadmapping Tool	Review article	Reduced lead times and low-cost customization
14	Liu et al. (2018) [85]	EBM process.	H13 tool steel	Energy consumption
15	Priarone et al. (2018) [128]	Assessment using a bottom-up approach	Ti-6Al-4V	Effect on global energy demand
16	Pan et al. (2018) [129]	FESEM/EDX	Iron, silicon, chromium, aluminum, nano-crystalline powders, polyethylene plastics	Yield strength and Young modulus analyzed
17	Jiang et al. 2019 [130]	Extrusionbased AM	Molten material	To reduce material consumption, production time, and energy consumption
18	Sardon et al. (2022) [132]	VP, FFF, DIW, PBF, and binder jetting	Polymeric materials	To reduce its carbon footprint

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