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Review

Examining the Progress in Additive Manufacturing in Supporting Lean, Green and Sustainable Manufacturing: A Systematic Review

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Abstract: The quest for waste reduction and the development of manufacturing processes that meet the economic, social and environmental requirements necessitate this study. Additive manufacturing is an emerging digital technology that can be used to seamlessly develop a product through material deposition in layers. The study aims to investigate the progress made in the development of additive manufacturing to support lean, green and sustainable manufacturing. The study employs a systematic literature review approach, specifically the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). A total of 158 articles identified from different academic databases that detailed empirical, conceptual and theoretical findings were reviewed, having matched the selection criteria. The outcome of the study indicated that additive manufacturing can be used to achieve waste reduction, reduction in emission generation and carbon footprints with significant energy and material conservation. The findings also indicated that the additive manufacturing process also boasts time- and cost-effectiveness during manufacturing compared to the conventional manufacturing technique. Although the process is energy intensive, careful selection of the suitable additive manufacturing process to be employed based on the requirements coupled with a proper product design may result in considerable energy savings at the preprocessing, processing or post-processing stages. This work adds to the understanding of additive manufacturing and contributes to the existing literature on the relationship among additive, lean, and green manufacturing. The study may help manufacturing organizations in their quest to minimize waste generation and achieve material and energy efficiency throughout their product lifecycles.

Keywords: additive manufacturing; green manufacturing; lean manufacturing; sustainable manufacturing; waste

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1. Introduction

Manufacturing organizations are constantly looking for ways to make their processes more efficient and capable using additive manufacturing (AM). AM uses a layer-wise manufacturing approach in which material builds upon the material, thus significantly reducing material and energy use [1]. Furthermore, AM can enhance the economic, environmental, and social development of corporate operations and is intrinsically more efficient than conventional subtractive production techniques [2]. The merits of the AM technique over the conventional manufacturing techniques range from freedom of design and flexibility to material conservation as well as cost- and time-effectiveness in manufacturing. These merits address the dynamic customer requirements, product customization, and the quest to reduce manufacturing lead times. AM also has the potential to support lean and green manufacturing for material conservation due to its capability for achieving material conservation and light-weightiness. Although the manufacturing sector is still the main driver of economic expansion, enhancing profitability is needed as the government, non-governmental organizations, society, and investors require organizations to reduce pollution and resource consumption. Thus, organizations worldwide are optimizing their processes and redefining the conventional business model to address several mega-forces and problems. A growing body of AM research has been conducted over the past ten years. However, AM is still relatively new, in the phase between conception and development, where many revolutionary technologies with the potential to succeed may fall short [3]. Thus, it must be widely developed and adopted to realize its full potential.

Although there is a proliferation of the adoption of AM by organizations, more research needs to be carried out to assess the benefits it offers to other philosophies, such as lean manufacturing and green manufacturing. Many organizations have adopted lean manufacturing and green manufacturing to guarantee the long-term viability of sustainability (economic, environmental, and societal performance) [4]. On the other hand, immense pressure from customers for organizations to improve environmental performance has also been a major driver for lean and green manufacturing adoption. Thus, many organizations are under obligation to maximize profitability while more effectively managing their operations and resource usage to minimize waste. It has become crucial to analyze the potential impact of AM on lean manufacturing and green manufacturing to improve sustainability since few studies have investigated this relationship. Another rationale for this study is the quest for waste reduction and the development of manufacturing processes that meet the economic, social and environmental requirements necessitated by this study. AM can open up the possibility of achieving a sustainable manufacturing environment if its potential is properly harnessed. Therefore, the technology complements the goals of LM and GM. For instance, it can help achieve materials, energy, cost and environmental conservation via its direct manufacturing approach with a reduction in the complexity of the value chain [5,6]. AM is increasingly gaining widespread attention in some industries such as the manufacturing, biomedical, automotive, aerospace, and rail industries, amongst others, due to its efficient and conservative way of manufacturing and its ability to deposit in layers or melt materials in a controlled manner using computer-aided software. Furthermore, AM offers flexibility, conceptualization, customization and fabrication components, especially those with intricate shapes without material or energy wastage, as well as time- and cost-effectiveness [6]. However, effective process design and optimization as well as proper selection of the right material that suits the intended application are necessary to optimally harness the benefits of AM.

The novelty of this study lies in the fact that the focus of AM, LM, and GM in relation to sustainable manufacturing is an upcoming area in the scientific literature, and only a few recent publications focus on different aspects of their combination. To the best of the authors' knowledge, no studies have been published covering the impact of AM on lean and green manufacturing, which affects sustainable performance. This is unexpected, considering how crucial AM is to the worldwide push to move away from traditional manufacturing and toward 3D printing. This study examines how AM promotes and supports LM and GM by recognizing the research gaps and the applicability of AM techniques.

The study aims to examine how the newer AM method can support older LM and GM methodologies. This study involves a systematic review to examine the literature and identify the complementary areas between AM, GM and LM. The objective is to attain more details about the work that has been carried out previously and to explore the current state without focusing on one particular organization. Thus, this enables us to gain an overview of how AM can be a way to attain improved LM and GM results.

This research seeks to answer the following questions:

(1) How should the impact of AM be conceptualized in LM and GM?
(2) What is the effect of AM, LM and GM on sustainable performance?

(3) What are the existing gaps and potential directions for future research at the AM and lean–green manufacturing interface?

This work adds to the understanding of additive manufacturing and contributes to the existing literature on the relationship among additive, lean, and green manufacturing. Business organizations are constantly looking for ways to reduce their carbon footprints as sustainability becomes a pressing concern. The expositions in this study may assist manufacturing industries in harnessing the potential of AM technology to achieve lean and green manufacturing. This will further promote waste reduction as well as economic, social and environmental sustainability through a reduction in the cost of waste, energy utilization and materials used for product development. As discussed in this study, AM has the potential to promote efficient material utilization and waste recovery by reducing product defects and converting materials that are out of specification into a raw material that can be used for other product development.

The study may also help manufacturing organizations in their quest to minimize waste generation and achieve material energy efficiency throughout their product lifecycles. For instance, manufacturing activities and techniques contribute significantly to greenhouse gas emissions and, ultimately, climate change. However, the use of additive manufacturing technology to replace energy-intensive conventional manufacturing techniques where suitable may lead to significant energy savings through a reduction in the fabrication or process steps during product development, thereby resulting in a reduction in the generation of greenhouse gas emissions. Compared to conventional manufacturing techniques, AM reduces energy usage by 25% and also reduces waste generation and material costs by 90% [7]. This study further highlights the benefits of AM, as well as its impact on lean and green manufacturing. The theoretical contributions from this study may be helpful to organizations in their quest for sustainability in terms of resources, cost and environmental conservation.

The remainder of the article is structured as follows: Section 2 covers the research methodology. The history of AM, LM, and GM implementation and the impact of AM on LM and GM and sustainability is covered in Section 3. Section 4 presents the discussion, and Section 5 concludes with recommendations for additional research.

2. Methodology

LM, GM, and AM articles were identified through a literature search using Google Scholar, Scopus and Web of Science databases. The synonyms for each term were listed first, followed by the identification of keywords, as shown in Table 1. The search process started by searching for single keywords such as lean, green, and additive manufacturing, and it was extended to include a combination of words. The Boolean operator ‘AND’ was used to combine the keywords, for example, LM ‘AND’ GM ‘AND’ AM. To identify different versions of the keywords, wild cards, * and ? were used.

The screening and article identification process was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). The guidelines outlined by Page et al. [8] in the PRISMA 2020 statement were used. A total of 1000 articles were identified from Scopus, 1000 from Google Scholar, and 1000 from Web of Science, giving a total of 3000 articles. A total of 2000 duplicate articles were eliminated before the screening process. In addition, 500 anonymous articles were removed, while 131 articles were eliminated because they were not written in English. The title and abstract were used to screen the remaining 369 articles, and 53 articles were excluded. The authors did not manage to retrieve 101 articles; hence, they were also eliminated. A total of 276 articles that remained were assessed for eligibility, and 118 articles were excluded as they focused on other industries that were not manufacturing. Finally, 158 peer-reviewed articles and reports whose focus and relevance match with the topic of discussion were synthesized to answer the research questions. The selected papers detailed empirical, conceptual and theoretical findings that matched the selection criteria. To minimize errors and bias in the selection process, the four authors of this study worked collaboratively to review and screen each record and report retrieved by matching them with the inclusion and exclusion criteria. Figure 1 shows the PRISMA method flow diagram indicating how the inclusion and exclusion criteria were implemented during the selection process.

Table 1. Synonyms and keywords for LM, GM and AM.

Search Aids	LM	GM	AM
Synonyms	Lean manufacturing Lean production Toyota production system (TPS)	Green manufacturing Environmental manufacturing Eco/ecological manufacturing Clean manufacturing Low-carbon manufacturing	Additive fabrication Direct digital manufacturing Freeform fabrication Solid freeform fabrication
Keywords	Just in Time Kaizen Kanban Jidoka Total Quality Management (TQM) 5 Why's Single Minute Exchange of Dies (SMED) 5S Visual Control Cellular manufacturing Total Preventive Maintenance (TPM) Value Stream Mapping (VSM) Poka yoke Takt time Heijunka Gemba Andon	Design for environment (DFE) Reduce, recycle and reuse (3R) Total-quality environmental management (TEQM) Life cycle assessment (LCA) Environmental emission control (EEC) Environmental management system (EMS) Green supply chain management (GSCM) Green purchasing Green procurement Green packaging	3D printing Rapid prototyping

The authors extracted the relevant information from each study included in the review, and they were further scrutinized, criticized and synthesized to derive a summary of the required evidence in a systematic way. Information was extracted on LM, GM and AM, with the outcome measures including the following: the impact of AM on LM and GM (primary outcome measure), the impact of AM on the environment (secondary outcome measure), the role of AM in waste reduction (secondary outcome measure), and the impact of LM, AM and GM on sustainable performance (secondary outcome measure). All the results obtained were compatible with each outcome domain for which information was sought. Sometimes, non-value-adding activities can result from other areas linked to manufacturing, such as poor layout, ineffective maintenance, supply chain disruption, and poor work and information flow, amongst others. However, this study assumes that there are no non-value-adding activities resulting from other areas linked to manufacturing apart from the ones from the three techniques of LM, GM, and AM. To assess the risk of bias in the included studies, the authors were paired to assess each study, and all conflicting areas in the two reports were resolved in a collaborative brainstorming session. The impact of the AM on LM and GM was tabulated and compared for each of the outcome measures. The study was limited to the synthesis of the selected articles to draw evidence and conclusions without statistical analysis of the information and evidence garnered from the literature.

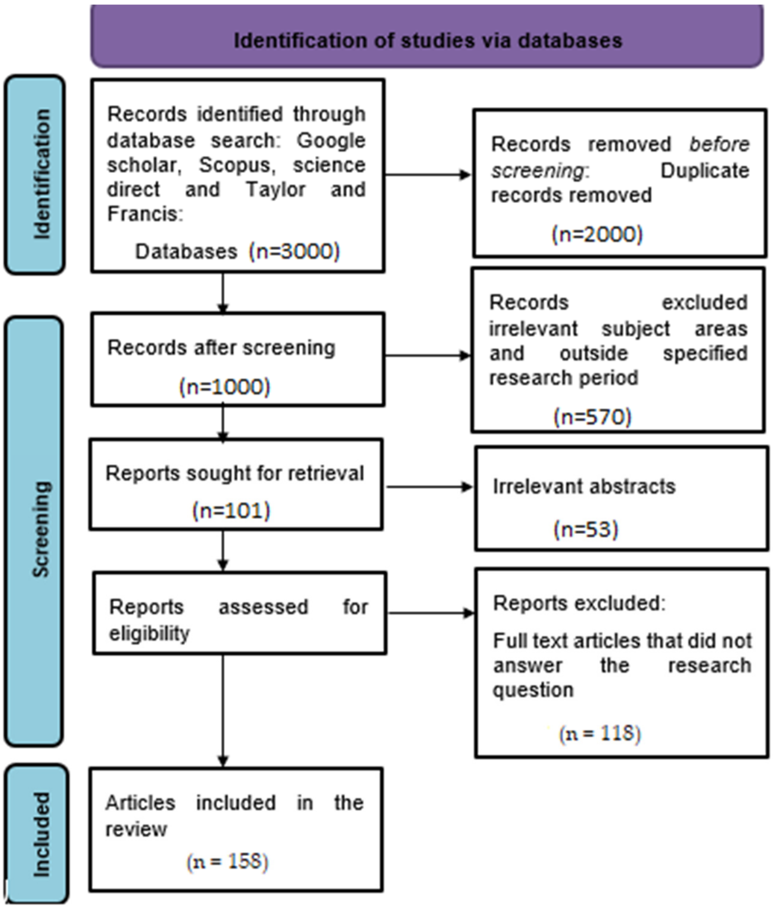

Figure 1. The PRISMA method flow diagram.

3. Literature Review

This section presents a systematic literature review on LM, GM, and AM. It establishes their interrelationship and presents an overview of their impacts on the environment and manufacturing industries.

3.1. Lean Manufacturing

Lean manufacturing (LM), also known as the Toyota production system, originated in Japan in the 1940s [9]. Its central tenet is to eliminate all non-value-added activities the customer is unwilling to pay for [10]. Not many manufacturing organizations can genuinely claim to have never heard of lean manufacturing, and ardent transformational leaders have persuaded internal and external stakeholders that lean manufacturing is the best course of action for their business. Lean transformation involves a complete transition of business operations, including how the supply chain functions, how executives guide, how managers organize, and how workers perform their daily tasks [11]. The objective of lean manufacturing is unquestionably to eliminate or minimize waste from the manufacturing process [12–15].

Any non-value-added activity that does not enhance the final product is waste. Waste may reduce resources and overall process cycle efficiency. Therefore, lean manufacturing seeks to provide a service or product that closely matches customer needs while reducing production processes that do not offer value [16,17]. Initially, Taichi Ohno defined seven types of waste: transportation, inventory, motion, waiting, overproduction, overprocessing, and defects [18]; however, two more types of waste have been added: underutilization of the creativity of employees and environmental waste [19]. Recently, researchers have explored the alignment of a conventional lean manufacturing philosophy with environmental objectives [20], studying complementarity and trade-offs [21,22].

3.2. Green Manufacturing

Green manufacturing (GM) is a methodology that focuses on reducing the negative environmental impacts caused by manufacturing processes [23]. The manufacturing sector is one of the major contributors to the greenhouse gas (GHG) emissions that cause changes in weather patterns and climate change. This ultimately results in an increase in temperature, extreme weather conditions, and other forms of natural disasters such as drought, heavy precipitation, flooding, wildfire, and cyclones, amongst others. To protect the environment from the impacts of manufacturing activities, the GM philosophy advocates for the use of raw materials that are friendly to the environment [24] and the utilization of processes that do not harm the environment, communities, employees, or consumers at any stage of the manufacturing process [25,26]. GM aims to minimize pollution and waste, Hines et al. [27] proposed eight GM wastes: excessive water usage, greenhouse gases, excessive power usage, pollution, excessive resource usage, eutrophication, poor health and safety, and rubbish. In addition, GM adoption should also reduce the consumption of raw materials to conserve them for future generations [28,29]. The excessive use of resources causes environmental degradation [30], and their fast depletion makes them scarce and expensive. To achieve this goal, GM uses practices such as recycle, reduce and reuse (3R), design for environment (DFE), life cycle assessment (LCA), green packaging, and green purchasing. Beyond the 3R approach of “recycle”, “reduce” and “reuse”, green manufacturing also introduces the strategies of “refurbish” and “re-manufacture” to optimize resource usage and extend the useful life of products. The essence is to minimize waste that can be further subjected to indiscriminate disposal that will add to the GHG emissions through recalling products that have reached their end-of-life back into service.

The concept of GM emphasizes the need for manufacturing industries to change their practices and business models as well as the focus of the stakeholders to tackle the impact of climate changes resulting from industrial activities. The concept seeks to address environmental concerns at the systemic levels [31]. The GM concept provides practical guidelines to achieve sustainable manufacturing practices within the manufacturing cycle through the supply chain and the customer base. Some of the GM strategies include the development of new materials, green packaging, green building, decarbonization of energy, development and implementation of digital innovation, circular economy and research and development (R&D) [31]. There is a huge potential to replace carbon- and energy-intensive strategies with less intensive ones. For instance, the use of titanium alloy can be used as a possible replacement for some steel-based alloys in the transport and aviation sector due to its high strength-to-weight ratio [32]. In terms of material development and processing, the use of innovative biomaterials has been reported [33]. The report of the World Economic Forum [31] indicated that the concept of green packaging can lead to 40% savings in the amount of energy consumed and 90% reduction in the amount of water required for production. In terms of green building, the EU, in the quest to achieve its carbon-neutral mandate of 2050, mandated the renovation of existing buildings and stipulates that all new buildings in the EU must produce zero-emission from 2030 with the installation of solar panels [34]. The essence of the decarbonization strategy is to achieve energy efficiency through energy savings. Conventional manufacturing is linear in nature, with a tendency for waste generation and environmental pollution. In contrast, GM emphasizes the principles of circular economy to achieve zero waste. The results of the adoption and implementation of the GM approach could manifest in the form of significant energy and natural resource savings, reduction in the global carbon footprint, optimization for production efficiency, and manufacturing sustainability and resilience, amongst others.

Various studies have reported on using GM to improve the performance of organizations. In Brazil, Soubihia et al. [35] reported that GM decreased waste, raw material consumption, and gas emissions. Green supply chain management (GSCM) in US manufacturing companies improved operational and environmental performance [36]. In Turkey, implementing GM enhanced social and environmental performance [37]. Afum et al. [23] reported improved social, economic, and environmental performances attained through adopting GM in Ghana. Yu et al. [38] indicated that GSCM causes improvements in operational performance measures, which are flexibility, delivery, cost, and quality in China.

3.3. Additive Manufacturing

The American Society for Testing and Materials (ASTM) defines AM as a process of joining materials layer by layer to make products using 3D model data [39]. AM processes can be classified based on the material consolidation strategy and type of raw materials used [40]. Figure 2 provides a summarized classification of AM processes.

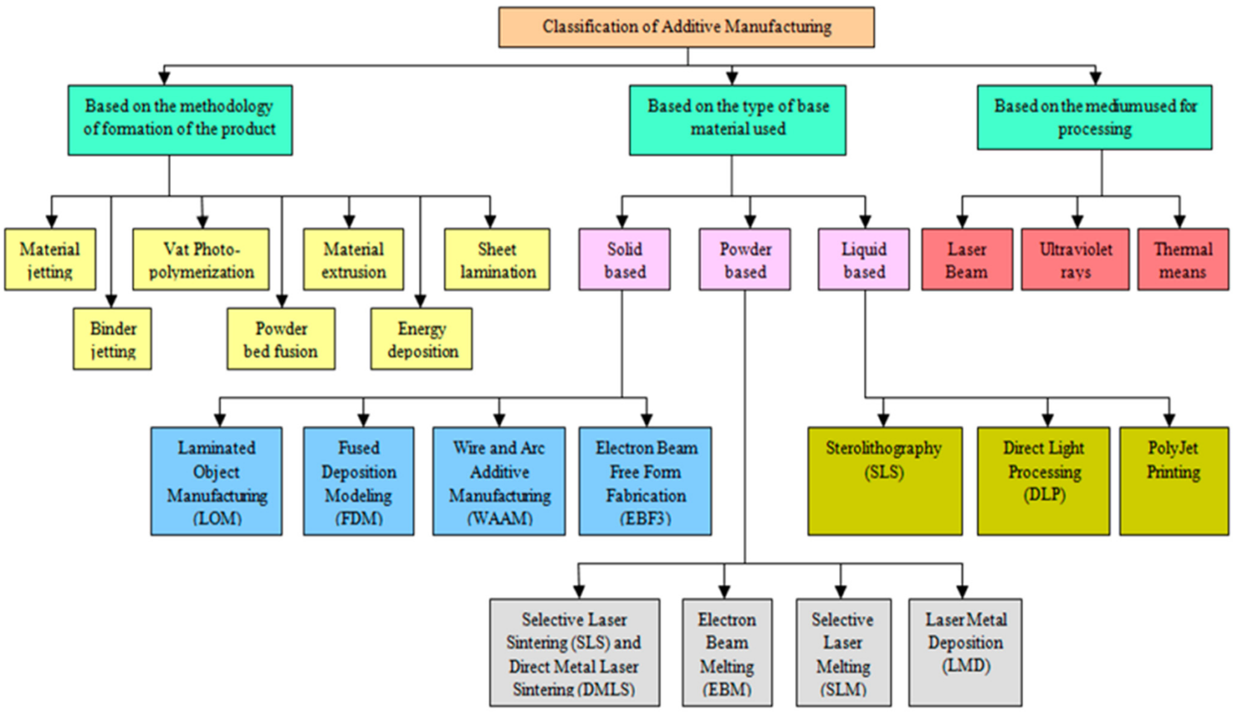

Figure 2. Classification of AM processes [40].

In comparison to conventional subtractive processes, AM has a lot of benefits. These include freedom of design, material efficiency, reduced environmental burden, reduced supply chain and resource efficiency [1]. Additionally, AM encourages recyclability and reuse by utilizing recycled materials as production inputs [41]. Through the AM technology, the parts needed for damaged or malfunctioning products on-site can be manufactured. This will promote fast maintenance turnaround time, thereby reducing lead time. AM also promotes maintenance and refurbishment operations and lengthens the product life cycle [42]. Since no tools or molds are needed for subsequent processing of the 3D computer-aided designs, it does not incur changeover expenses, and digital documents of designs can be quickly exchanged, making it easier to modify and personalize parts and products [2]. However, some of its limitations include the selection of the appropriate build speed, product development at high resolution, biocompatibility and mechanical properties of fabricated parts, the need for post-processing for some parts, and the composition of multi-material parts, amongst others [43].

3.4. Additive Manufacturing and Green Manufacturing

AM can be used to manufacture products using biodegradable materials that are environmentally friendly and can be disposed of at the end of life [44]. Puppi and Chiellini [43] presented an overview of the literature on the usage of bio-degradable products in the medical industry.

Typical bio-degradable polymers used in AM include polylactic acid (PLA), polyvinyl alcohol (PVA), polyhydroxyalkanoates (PHA), hot isostatic pressing (HIP), and polyethylene terephthalate (PET) [44]. Polymeric materials find applications in various biomedical areas, such as scaffolds for bone regeneration, processing of digital medical images, 3D anatomical models and surgical training, surgical equipment, prosthetics and implants, tissue engineering, in vitro tissue modelling, and drug discovery, amongst others [33,43].

Some of the requirements of the AM materials used for biomedical applications include biocompatibility, as well as structural and functional requirements tailored to specific applications. For instance, biomedical devices interfacing with cells and used in regenerative processes should provide biochemical activities that can influence the behaviors of the cells. AM has an advantage over other processing techniques in biomedical applications due to its potential to control the major compositional, structural, and functional parameters of the polymeric system [44].

Guerra et al. [45] designed a novel AM machine for making a bio-degradable stent. The AM machine uses the fused filament fabrication method as well as polycaprolactone (PCL), a biodegradable polyester, as the material. The performance evaluation of the AM machine was conducted by studying the effect of fluid flow, nozzle temperature, and printing speed on the accuracy of the developed product. The results obtained show that temperature and flow rate strongly influence the accuracy of the developed product over the printing precision. Oladapo et al. [33] reported on the use of biopolymer and calcium phosphate composites of carbon apatite in polylactic acid (with a PLA/cHA ratio of 95:5 and 80:20 m/m as scaffolds for bone regeneration. The printing was performed using the following process parameters: print speed (20 mm/s), layer thickness (0.3 mm) and deposition angle (0–90°). The results obtained indicated that the apparent porosity of the 5% and 20% of cHA scaffolds gave a percentage porosity of about 62% and 41%, respectively. This shows that it is possible to produce 95/5 PLA/cHA composite scaffolds via AM technology.

Jiang et al. [46] studied the production of scaffolds using bio-degradable iron-based reinforced polymers for bone regeneration. The PLA composite scaffolds were produced using AM technology, specifically the fused filament fabrication (FFF) process using two different types of iron-based powders, namely stainless steel 316L and pure iron. The outcome of the study shows that the scaffolds were manufactured with a precise pore dimension of 0.80 ± 0.08 mm, having a homogenous distribution of iron-based powders in the PLA matrix. Furthermore, the results also indicate that the PLA/Iron scaffold has high in vitro degradation resistance, high hydrophilic wetting behavior and cytocompatibility, thereby demonstrating its feasibility for application in bone or tissue engineering.

Another emerging area of research involves the additive manufacturing of natural fibers. Mangat et al. [47] conducted an experimental study on using natural fiber to produce structures for biomedical applications. The authors investigated the mechanical properties and bacterial characteristics of chemically treated waste natural fiber (such as silk fiber and sheep wool fibers) and inserted three-dimensional structures (NFi3DS) produced using PLA as the matrix and fused filament deposition (FFD) as the AM method. The outcome of this study indicates the suitability of embedded structures for scaffold-based biomedical applications. The outcomes of these studies indicate the suitability of AM technology for the production of biodegradable materials and its feasibility for replacing conventional materials without sacrificing the functional requirements.

Another merit AM technology offers is its flexibility and freedom of design. The design freedom provided by AM allows for products with improved functional performance [48]. For example, Böckin and Tillman [49] reported the re-design of a truck engine to lightweight parts that consume less material. The study involves the experimental redesign of a truck engine for AM along with the test prints, as well as the environmental impact assessment to investigate the environmental impacts of AM technology. The outcome of this study indicates that high-density materials, such as nickel-alloys and stainless steel, will contribute to high environmental impacts and should be avoided, while low- to medium-density materials, such as low-alloy steel, will produce a lower environmental impact for the AM technology.

In the aerospace and automotive industry, lightweight parts produced with AM technology help to reduce weight, thereby increasing fuel efficiency [49]. AM can eliminate assemblies by producing consolidated parts, thus eliminating the intermediary supply chains, resources and energy used to produce fasteners when conventional processes are used [48]. Eliminating these intermediaries and assemblies will make the manufacturing process more cost- and time-effective than the conventional manufacturing system. Topology optimization has produced high-performance designs using fewer materials [50]. The freedom of design in AM allows the manufacture of products with specialized features, such as integrated sensors or conformal cooling structures [51]. This helps improve the products' functional performance and makes them more energy efficient in their lifecycle.

Repair and refurbishment are important strategies for remanufacturing as they allow end-of-life products to be revived. AM can be used to refurbish and repair worn-out equipment [52]. Direct energy deposition (DED) is a group of AM processes that offer the capability to repair worn-out metallic parts. Leino et al. [53] reviewed the use of AM to repair damaged parts and how this contributes to a circular economy. By implication, this will reduce the amount of waste generated and, ultimately, the amount of GHG emitted through indiscriminate waste disposal and landfilling. Shrivastava et al. [54] studied nickel-based aerospace component remanufacturing using DED. Their study concluded that DED is a cost-effective solution for repairing high-value components. Saboori et al. [55] presented an overview of the usage of the DED process in the repair of metallic components. The outcome of these studies further lends credence to the fact that AM technology can be used to achieve a circular economy.

The global increase in plastic waste is a growing concern as it threatens aquatic life. AM offers a solution to this challenge by recycling polymer-based products, thus contributing to sustainable manufacturing [56]. For instance, fused deposition modelling (FDM) is a popular polymer-based AM process that allows the processing of recycled polymers [42]. Rahimizadeh et al. [57] conducted a study involving the recycling of materials from fiberglass wind turbine blades. The outcome of the study indicated that FDM is suitable for material recycling.

The application of AM technology for component development in the automotive, rail and aerospace sectors have been reported [58–62]. This can lead to significant savings in the amount of energy consumed due to the development of lightweight components, as well as a reduction in the amount of emissions generated and increase in the environmental friendliness in the transport sector.

3.5. Additive Manufacturing and Lean Manufacturing

AM has the capability of manufacturing parts to net shape [63]. The layer-wise addition manufacturing strategy enables full utilization of high-value material, resulting in less wastage [64]. This is different from traditional subtractive manufacturing processes in which parts are manufactured through material removal. Another advantage of AM is that products are manufactured directly from digital models. This digital manufacturing strategy helps minimize errors that may arise from traditional manufacturing processes, resulting in increased quality of products [1]. Also, products can be kept in the form of digital files and manufactured on demand at the point at which they are required. This helps to reduce the environmental burden associated with manufacturing and storing physical inventory. Manufacturing products on demand and on-site is useful in eliminating the pollution associated with the transportation of products from one point to another [65]. This is in line with the just-in-time (JIT) lean production system that focuses on the production of the product quantity needed at a time rather than producing goods and supplying them from stock. This prevents overproduction, minimizes waiting time and saves resources due to a streamlined production system. It also reduces the capital tied down on stock and decreases the chances of product defects. AM supports the JIT lean system by aligning the raw material orders with the production schedules. This strategy can be employed to increase production efficiency and reduce waste as well as the inventory cost. Furthermore, AM contributes to the reduction in plastic waste by using only the material required for the final component manufacturing [2].

3.6. Impact of Additive Manufacturing on Environmental Performance

AM is an emerging technology that has the potential to minimize the adverse environmental effects caused by manufacturing organizations [49]. Its benefits include the fact that light part weights can be produced due to the redesigning of components [49], reduction in the number of components, which makes assembly and disassembly easier [66,67], and lower cost of production for complex products [2,68]. Furthermore, AM caused a reduction in material losses and transportation of parts [3,69], a possibility to produce spare parts [49], a shorter process method, and reduced supported tooling [70–72].

However, this technology is still evolving, and some of its benefits on environmental issues and consumption of resources are still uncertain [49]. The potential of AM to reduce weight could result in a reduction in fuel usage. Additionally, the deposition of materials layer by layers through AM reduces waste and greenhouse gas emissions [71,72]. Tang et al. [73] obtained a 64% decrease in CO_2 emissions using AM rather than the conventional computer numerical control (CNC) machine. Thus, AM is considered a clean manufacturing method [71,72] and is more sustainable than conventional manufacturing methods [1].

The study by Bockin and Tillman [49] indicated that AM currently has a negligible-to-medium impact on improving environmental performance as it uses high amounts of energy. The authors conducted a lifecycle assessment of automobile engine metal parts produced via metal bed fusion. The outcome of the study indicates that the use of AM resulted in significant environmental improvements through a reduction in weight reduction, leading to a decrease in the impacts of the use phase. The results further show that the use of AM technology in the automotive industry can only reduce the life cycle impacts if clean electricity is used during the printing process. The author suggested that AM technology may not be sustainable in the short term or short scale but will be more sustainable when deployed on a large scale for high-volume product development with the use of low-alloy steel material.

One of the major differences between the AM and conventional manufacturing process in terms of energy consumption is that the energy consumed during AM is absorbed directly by the material under development. Thus, this minimizes energy losses in the form of heat or heat transferred to the machine or cutting tool, as in the case of conventional manufacturing. Although the energy consumed during the AM process may increase with an increase in the product complexity and need for processing, the need for a cooling system is eliminated compared to conventional manufacturing. In conventional manufacturing, the heat loss transferred to the machine tool can reduce the useful life and promote the development of residual stresses that may affect the functional requirement of the cutting tool as well as the quality of the final product. Energy is more conserved in the AM process, and this makes the process less energy-intensive compared to conventional manufacturing. The lower the energy intensity of the manufacturing process, the more sustainable and environmentally friendly it is, and vice versa. Many environmental improvements can still be realized in the future by adopting clean electricity for the AM process. In addition, Nagarajan and Haapala [74] noted a need to identify clean energy, minimize electricity transmission loss, and reduce energy use during processing.

3.7. An Overview of the Impact of AM, Lean and Green Manufacturing Studies Conducted for Manufacturing Organizations

Table 2 presents an overview of the impact of AM on lean and green manufacturing.

Table 2. Impact of AM on lean and green manufacturing.

Author	Focus	Description	Impact of AM on Lean/Green Manufacturing	How the AM, LM and GM Impact Sustainable Manufacturing
Ford and Despeisse [2]	Raw materials and product development	An investigation of the deployment of AM from a life cycle assessment to enable sustainability benefits.	An increase in the efficiency of raw materials. Since additive manufacturing calls for many kinds of material inputs, beneficiation of materials with less toxic effects, waste, non-value-added activities and byproducts being removed from the waste stream, and less intense energy utilization.	The ability of the resulting geometry to meet performance requirements, dematerialization of products, streamlined assemblies, goods, and parts, modular design's flexibility to be upgraded, and democratized method of design.
Tang et al. [73]	Energy conservation	Design of a life cycle assessment framework that incorporates the design stage to reduce the environmental effect of the binder jetting AM process.	The binder jetting process produced an optimal part that used a significantly reduced energy and produced lower amounts of carbon dioxide compared to the CNC milling machine.	The sustainability in manufacturing arises from the fact that energy and resources conservation can be addressed from the design stage to reduce the impact of the manufacturing process on the environment.
Ching et al. [75]	Energy, materials and cost conservation	A thorough examination of the literature to identify the sustainability functions that Industry 4.0 uses to support sustainable production.	The environmental aspect of manufacturing sustainability benefited from Industry 4.0 by the reduction in waste across the value chain and reduced the quantity of material and energy resources utilized.	Reduced manufacturing costs also result in more customer-focused production and higher manufacturing profit margins, both of which support the growth of networks that generate economic sustainable value.
Böckin, and Tillman [49]	Energy efficiency through weight reduction	Environmental assessment of additive manufacturing in the automotive industry.	In the aerospace and automotive industry, lightweight parts produced with AM help to reduce weight, thereby increasing the fuel efficiency.	The design of lightweight parts which consume less material makes the AM process sustainable. The quest for lightweight parts that consume less material will also result in less energy consumption and less GHG emissions.
Chandra et al. [76]	Product quality and environmental performance	Utilization of the complex proportional assessment (COPRAS) and stepwise weight assessment ratio analysis (SWARA) multicriteria decision making process to select the most sustainable AM process.	AM improves product quality, product ecological performance, market stability and reduces production cost	The sustainability of AM is largely affected by variables like energy consumption and environmentally friendly, waste-free manufacture.
Frăţilă and Rotaru [65]	Efficient resources utilization and improved waste management.	The design of a predictive assessment technique to assess the environmental effects for two AM technologies (fused deposition modeling (FDM) and selective laser sintering (SLS)) and computer numerical control (CNC) milling and taking into account the energy, fluids and materials required during a product's manufacturing process, as well as waste materials and recycled components.	Reduced production cost, energy and raw material use and improved waste management.	Improved worker safety and health, efficient material and energy use, industrial waste management, low manufacturing costs, avoidance of toxic emissions and materials.

Table 2. *Cont.*

Author	Focus	Description	Impact of AM on Lean/Green Manufacturing	How the AM, LM and GM Impact Sustainable Manufacturing
Ghobadian et al. [3]	Environment and resources conservation	An analysis of the potential of additive manufacturing to support LM, thus enhancing sustainability and innovation for organizations.	AM decreases physical environmental degradation, lead time, cost, waste and increases product's quality.	AM lowers fuel usage, increases product durability, productivity, and create new employment opportunities.
Huang et al. [77]	Lean supply chain	An analysis of the effects of AM on society from a technological view.	A decrease in the need for packaging, waste shipping, and storage, and increase the effectiveness of a lean supply chain.	AM improves the wellbeing and health of people through creating specialized surgical implants and assistive devices that are tailored to each patient's needs.
Kellens et al. [67]	Effective energy and raw material utilization	A summary of the life cycle inventory data and a comparison of the environmental effects of several AM technologies.	A reduction in energy and raw material usage.	AM results in fuel usage reduction, electric power savings, as well as weight reduction.
Naghshineh et al. [78]	Effective energy and raw material utilization, socio-economic benefits and localization	Analyzing the social effects of AM technology that have an effect on the industry stakeholders involved in various product life cycles.	AM lowers the amount of energy and raw materials used in manufacturing and encourages recycling and reuse.	AM help to maintain their cultural heritage since the community can manufacture the components and goods they require, and there will be less outside influence on their native cultures. Additionally, AM improves access to employment, income, skills, and disaster mitigation with the ability to produce goods, commodities, and replacements quickly.
Priarone et al. [79]	Effective energy and raw material utilization, as well as environmental conservation	An assessment of the energy use and CO_2 emission between the traditional machining and wire arc additive manufacturing techniques.	Reduction in the usage of raw materials.	When the wire arc additive manufacturing based strategy is employed, there has been a notable decrease in resource/energy consumption and CO_2 emissions.
Touriki et al. [80]	Waste elimination, efficient resources usage and recovery options	Developed a framework for integrating smart, green and lean manufacturing.	AM allows for elimination of waste, Efficient usage of resources, the possibilities of repair, refurbishment, remanufacturing actions, and recycling of products.	Improved environmental performance and increased resource efficiency.
Niaki et al. [63]	Efficient design, product development and resource conservation	Identified the concepts behind the application of AM in different industries and ranked them.	The design freedom offered by AM allows for lightweight designs which lead to reduced energy, tool less manufacturing and resource efficient production.	Time- and cost-saving, particularly product development.

Table 2. *Cont.*

Author	Focus	Description	Impact of AM on Lean/Green Manufacturing	How the AM, LM and GM Impact Sustainable Manufacturing
Belhadi et al. [81]	Energy, waste and lifecycle management,	Used structural equation modelling to establish the linkage between big data analytics, lean six sigma and green manufacturing.	Application of AM in manufacturing results in improved energy efficiency, lifecycle management, waste elimination and reconfigurable manufacturing.	Waste elimination, increased savings, reduced environmental impact.
Agnusdei et al. [82]	Product and process sustainability	Conducted a systematic review on the role of AM in sustainability. Used statistical tools to identify the most ranked articles and key words on the sustainability of AM.	On demand manufacturing, cost effectiveness, high-performance designs for improved quality, reduced energy consumption and reduction in waste.	Elimination of waste, reduced production costs and improved environmental performance.
Ghobakhloo and Fathi [83]	Energy reduction and improved economic performance	Examining the impact of Industry 4.0 towards energy sustainability.	The application of AM has the potential to reduce energy consumption by 20%.	Reduces energy cost, will lead to improved economic performance.
Belhadi et al. [81]	Improved value chain and sustainability	The relationship between industry 4.0 methods such as AM and sustainable performance.	AM reduces raw material consumption, time to market, production cost, minimizes the logistic processes, reduces waste, can reduce logistics and transportation energy.	Improved economic, social and environmental performance.
Kumar and Chhabra [84]	Innovative design	Developed an AM framework for automatic design of orthotic devices using topology optimization. The framework can be used to design and manufacture orthotic devices which are lightweight and optimally designed.	AM allows for design optimization of orthotic devices to improve functionally while reducing weight and material consumption.	Improved quality of life of patients with orthotic patients through customized rehabilitation. Costs savings and improved innovation in the manufacture of orthotic devices.
Liu et al. [85]	Material sustainability	Presents a review on sustainable materials which can be used for additive manufacturing in the construction sector. The review ended by presenting the research gaps in AM using sustainable materials.	The application of AM reduces material consumption, waste and time in construction.	AM allows for the use of sustainable materials which are environmentally friendly. It also reduces the materials used in construction.
Majeed et al. [86]	AM sustainability and product life cycle	Developed a framework of big data analytics in smart sustainable additive manufacturing. The framework was produced by combining data analytics, additive manufacturing and sustainable smart manufacturing technologies. it is useful at the beginning of life (BOL) stage of the product life cycle.	Improved quality, reduced lead time and increased operational efficiency in the production of AM parts.	Improved energy efficiency, cost savings and improved decision making at the beginning of life stage.

4. Results and Discussion

This section discusses the findings from the literature about the role of AM in reducing green wastes, its impact on green and lean manufacturing, and how it leads to sustainable performance, as well as the overlap among lean–green–additive manufacturing.

4.1. Role of AM in Reducing Green Wastes

AM has made a significant contribution to minimizing environmental damage by reducing green waste. Although the issue of energy consumption needs to be addressed, most of the green waste can be eliminated through AM. Table 3 shows the relationship between AM and green waste.

Table 3. Role of AM in reducing green waste.

Green Waste	Contribution/Impact of AM	Reference
Excessive water usage	The concept of green packaging through AM can lead to a 90% reduction in the amount of water required for production.	The report of the World Economic Forum [31].
Greenhouse gases	Reduces the CO_2 emissions due to the methods used and reduced transportation.	Javaid et al. [1], Yang et al. [71]
Excessive power usage	Reduction in the consumption of electricity.	Bockin and Tillman [49], Ingarao et al. [70], Yang et al. [71], Nagarajan and Haapala [74], Ghobakhloo and Fathi [83].
Pollution	Pollution is reduced through the use of biodegradable, organic, non-toxic substances.	Javaid et al. [1].
Excessive resource usage	Less resource usage as the exact amount is used.	Javaid et al. [1], Ingarao et al. [70]
Environmental impacts	AM has the potential to reduce environmental impacts such as abiotic depletion, acidification, global warming, eutrophication, terrestrial, marine and aquatic ecotoxicity	Shuaib et al. [87]
Poor health and safety	AM increases the automation levels, making the process safe and saving lives.	Javaid et al. [1].
Rubbish	Reduces the amount of rubbish as the thermoplastic and other materials can be recycled and reused.	Javaid et al. [1], Yang et al. [71], Colorado et al. [88].

Despite the benefits of AM with respect to waste reduction, it is important to mention that not all materials can be manufactured via additive manufacturing and that not all AM materials can be easily recovered or recycled. For instance, polylactic acid (PLA), a biopolymer made from plant materials, finds applications as AM filament feedstock material but does not degrade under ordinary conditions, thereby constituting waste at the end of its life [89]. Furthermore, AM also produces waste in the form of failed prints, destructive prototypes, and leftover materials [90–93]. The properties of recycled materials such as plastic are often affected by factors such as ultraviolet radiation, contamination during waste collection, and the degree of degradation during processing [94]. In addition, the volume of waste generated may increase for AM techniques such as wire-based direct energy deposition, where materials must be machined to produce a near-net shape [1]. When producing highly complex parts with AM, support structures are used to ensure that the desired shapes are attained. However, these support structures are discarded after the printing process [95]. This leads to material wastage. Another concerning issue is the toxicity of some of the AM materials. For example, powder bed fusion processes such as selective laser melting utilize metal powders that are toxic and highly flammable [48]. Also, photopolymers that are used in processes such as stereolithography release volatile organic compounds that are toxic in nature [96]. It should also be noted that the process of producing metal powders is energy-intensive in nature [97]. This raises environmental concerns, and there is a need for further study on the usage of sustainable materials.

Most thermoplastics used in extrusion processes such as fused deposition modelling are often difficult to effectively recycle. This is because of contamination and degradation that occurs during the printing process [98]. The same also applies to metal powder, which is also prone to contamination, making it difficult to recycle [99]. Also, when printing metal powder, some of it is partially melted and oxidized, and its structure and composition is altered. This further complicates the recycling process.

On the other hand, the usage of biodegradable materials such as PLA, PHAs and cellulose-based materials can address most of the concerns associated with conventional AM materials. However, the biodegradability of these materials depends on specific environmental conditions such as temperature and humidity. Also, the mechanical properties of these materials are limited [98]. Hence, there is need for further studies on improving the mechanical properties while maintaining their environmental benefits.

Although the AM process is energy intensive, the careful selection of the suitable additive manufacturing process to be employed based on the requirements coupled with a proper product design may result in considerable energy savings at the preprocessing, processing or post-processing stages. Furthermore, effective process design and optimization as well as proper selection of the right material that suits an intended application are necessary to optimally harness the benefits of AM.

Tables 4 and 5 present the impact of AM in green and lean manufacturing, respectively, while Table 6 presents the impact of LM, AM and GM on sustainable performance. The sustainable performance shown in Table 6 uses three key indicator metrics, namely economic, social and environmental performance.

Table 4. Role of AM in green manufacturing.

Concept	Impact of AM in Green Manufacturing	Reference
Use of biodegradable materials.	Products manufactured with AM using biodegradable raw materials can decompose naturally without negatively impacting the environment.	Pakkanen et al. [44], Qin et al. [100].
Remanufacturing.	AM allows for remanufacturing of worn-out metal-based parts so that they are restored to their original state, thus reducing the environmental burden associated with manufacturing new parts.	Wilson et al. [101], Rahito and Azman [52], Phuluwa et al. [102].
Recycling of polymer-based products.	AM allows for the recycling of polymer-based products, thus reducing the quantity of plastic waste in landfills and the environment.	Pakkanen et al. [44], Gaikwad et al. [103].
Reduction in waste through optimized designs that use less material.	The design freedom offered by AM allows for part designs that use lesser material when compared to conventional manufacturing technologies.	Lopez Taborda et al. [104]
Producing lightweight parts with less environmental impact.	AM allows for the manufacture of high-performance designs that result in reduced carbon emissions.	Orme et al. [105], Ganesh Sarvankar and Yewale [106]
Elimination of assemblies through consolidation of parts. This reduces the environmental impact associated with producing fasteners.	AM allows for the manufacture of parts that are already assembled, thus reducing the number of sub-assemblies.	Yang et al. [71], Knofius et al. [107].
Energy-efficient products with improved functionality.	AM allows for the manufacture of high-performance products that use less energy.	Hettesheimer et al. [108]
Producing parts from digital models, thus eliminating production tools. This reduces the environmental impact of manufacturing tools.	AM eliminates the use of tools by producing parts directly from CAD design models.	Javaid et al. [1], Taddese et al. [109]
Eliminating the environmental burden associated with transportation of parts by producing parts on demand and on site.	Producing parts on site and on demand eliminates the need for outsourcing and transportation.	Javaid et al. [1]

Table 5. Role of AM in lean manufacturing.

Concept	Role of AM in Lean Manufacturing	Reference
Improved operational efficiency by using a shorter process chain.	AM shortens the process steps to manufacture products since parts are produced directly from digital models.	Yusuf et al. [110] Jamwal et al. [111]
Reduced rejects by eliminating errors associated with using conventional manufacturing technologies.	Human errors are reduced by employing digital manufacturing.	Javaid et al. [1]
Reduced rejects through the usage of tools and equipment with improved performance.	AM allows for the manufacture of intelligent products with embedded sensors. This results in improved quality control.	Hossain et al. [51]
Improved manufacturing efficiency through AM-based tools and molds with specialized features.	AM allows for the manufacture of high-performance tools with improved features such as conformal cooling systems in injection molding tools. This results in improved quality and reduced lead time.	Hu et al. [112], Muvunzi et al. [113,114].
Elimination of physical inventory through the usage of digital inventory.	Inventory can be stored in the form of CAD designs as opposed to the storage of physical inventory, which ties up capital and storage space.	Knofius and Heijden [115].
Reduced waiting time for spare parts by producing them locally, on demand and on site.	Parts can be produced at the point of need. This eliminates the waiting time associated with outsourcing spare parts. Reduced transportation through localized manufacturing.	Gonzalez-Varoa et al. [116], Attaran [117]
Eliminating overproduction by producing customized parts.	AM allows for the manufacture of customized products.	Javaid et al. [1]

Table 6. The impact of LM, AM and GM on sustainable performance.

References	Economic Performance	Social Performance	Environmental Performance
Lean Manufacturing			
Dey et al. [118], Singh et al. [119]	Cost reduction, productivity, sales and business growth.	Improved safety, working conditions, labor relations, morale and work pressure.	Waste reduction, pollution reduction, recycling.
Singh et al. [119], Ghaithan et al. [120]	Cost reduction, improves profit, improves efficiency.	Improved safety, working conditions, labor relations, morale and work pressure.	Decreased waste (solid, liquid and gases), reduced consumption of toxic material and energy usage.
Ghaithan et al. [120], Wu et al. [121]	Cost reduction, improved profits.	Improved social awards and social presence.	Decreased waste (solid, liquid and gases), reduced consumption of toxic material and energy usage.
Ghaithan et al. [120], Garza-Reyes et al. [122]	Cost reduction, improved profits.	Potential for job creation.	Reduced material use, pollutant emission, energy consumption and non-product output.
Wu et al. [121]	Improved return on sales (ROS), return on assets (ROA) and reduced costs.	Potential for job creation.	Reduced waste (air, wastewater and solid), reduced use of harmful material and energy consumption.

Table 6. *Cont.*

Vinodh et al. [19]	Reduction in the cost of production.	Potential for job creation.	Reduced waste (air, wastewater and solid), energy use and raw material use.
Nawanir et al. [123].	Improved market share, product quality, flexibility, profitability and order delivery, reduced waste treatment fees, costs and environmental accident fees.	Enhanced safety and health, improved relationship with stakeholders and community, improved quality of living of the surrounding community and the working conditions.	Reduced waste (air, wastewater and solid), decreased energy consumption, improved compliance with the environmental standards and reduced material usage.
Green Manufacturing			
References	**Economic Performance**	**Social Performance**	**Environmental Performance**
Afum et al. [23]	The adoption of GM is positively related to increase in profits, sales, return on investment (ROI), return on equity and return on asset.	GM implementation led to improvements in quality of nearby community, safety and health of workers, job satisfaction, and stakeholder and community relationships.	GM implementation led to a decrease in the consumption of hazardous materials, environmental accidents, environmental impacts and increased compliances to the environmental standards.
Rusinko [124]	GM reduces the usage of resources and recycles waste, leading to the reduction in manufacturing cost.	The reduction in waste and pollution lead to improved community and workers' health and safety.	Recycling of waste reduces resource consumption.
Sezen and Cankaya [38]	Improvement in the manufacturing time and cost effectiveness.	Green manufacturing led to increased occupational health and safety.	GM reduce environmental waste and environmental impact.
Famiyeh et al. [125]	Improved quality, delivery, flexibility, and reduction in cost are obtained as a result of implementing GM.	Improvement in environmental performance led to increase safety and health, reduction in community complaints.	Enhanced overall environmental performance is attained when organizations perform in a green way.
Mafini and Loury-Okoumba [126]	Results attained include improved delivery, quality, product line, capacity utilization and decreased inventory.	Decrease in scrap rate will contribute to decrease in solid waste, therefore, leading to decreased complaints from nearby customers.	Decrease in scrap rate was attained.
Yu et al. [38]	Improvements in flexibility, cost, quality and delivery was realized through GSCM adoption.	Potential for job creation.	Reduction in emissions, wastewater, hazardous material consumption and solid waste.
Eshikumo and Odock [127]	Organizations that adopt GM practices such as recycling reduced their production costs. Cost reduction and increase in ROI were attained through GM implementation.	The reduction in negative environmental impacts increases the safety and health of workers.	Adoption of recycling, emission reduction and energy reduction practices reduce the negative environmental impacts. GM led to the reduction in environmental impact, material used, energy usage during transportation.
Ivan et al. [128], Pakkanen et al. [44]	Eliminating of overproduction by producing parts on demand.	Potential for job creation.	AM can process biodegradable materials which decompose without negatively impacting the environment.

Table 6. *Cont.*

Thomas et al. [129], Rahimizadeh et al. [57]	Reducing supply chain costs.	Potential for job creation.	Polymer materials used in AM can be recycled. This reduced the quantity of polymer waste in the environment.
Knofius and Heijden [115] Sahu et al. [130]	Reduced transportation through localized manufacturing.	Potential for job creation.	AM can help to reduce E-waste by transforming it to sustainable filaments.

Figure 3 presents the lean–green–additive manufacturing overlap. The overlap shows complementary areas between LM, GM, and AM that are geared toward sustainable performance. The figure indicated that the combination of the lean–green–additive manufacturing approaches could be used to achieve a reduction in the manufacturing lead time, waste reduction, reduction in energy usage, product quality improvement, improvement in safety and health-related issues, reduction in pollution, decrease in inventory, and a reduction in the production costs. Sometimes, non-value-adding activities can result from other areas linked to manufacturing, such as poor layout, ineffective maintenance, supply chain disruption, and poor work and information flow, amongst others. However, this study assumes that no non-value-adding activities result from other areas linked to manufacturing apart from the ones from LM, GM, and AM.

The environmental sustainability of AM is still an open debate in the literature [1]. However, there are several ways in which AM clearly contributes towards green manufacturing. Firstly, AM allows for the manufacture of objects to their net shape using a consolidated approach without tooling. When compared to traditional subtractive processes, this reduces the amount of material in manufacturing products [88]. Also, the environmental burden associated with making production tooling is eliminated [1]. The net shape approach helps in the development of optimized product designs with improved functionality [104]. Such designs ensure products are lighter in weight and more energy efficient, thus reducing the carbon footprint. The design freedom offered by AM enables the production of consolidated parts [71]. This reduces the environmental impact associated with producing fasteners and separate assemblies.

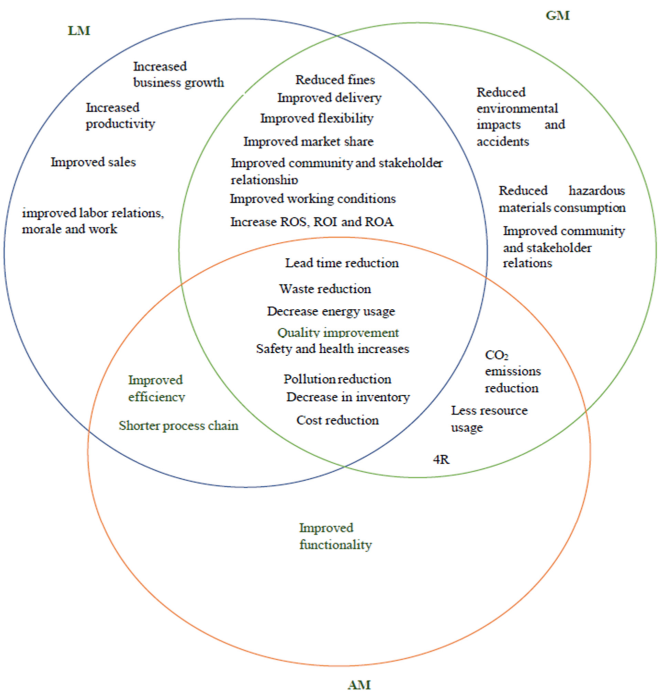

Figure 3. Lean–green–additive manufacturing overlap.

4.2. Quantitative Analysis of the Impact of AM, Lean and Green Manufacturing

Kellens et al. [67], in their work on the environmental impact of additive manufacturing processes, found environmental and energy improvements between 36 and 75%. Wilson et al. [101], while investigating the remanufacturing of turbine blades by laser direct deposition, found reductions in the carbon footprint and energy savings by approximately 45% and 36%, respectively, compared to the replacement of the turbine blades with a new component.

Existing studies that considered the cradle to gate indicated that the weight of a product manufactured via AM can hypothetically be reduced to approximately half via topology optimization, thereby resulting in a 25–58% reduction in the energy consumed and 60% reduction in climate-change-related impact during manufacturing [73,131,132]. For automotive and aerospace parts manufactured via AM, existing studies indicate the feasibility of energy savings during the use stage, resulting in a reduction in the environmental impact by 11–20% over the life cycle [70,133]. Reis et al. [134] found a 12–47% reduction in the environmental impact for different part geometries produced using wire arc additive manufacturing (WAAM) due to its suitability for manufacturing complex part geometries when compared to CNC milling. Similarly, Yang et al. [135] achieved an average reduction of 20% in the environmental impact by reducing the assembly operations for the design of a train floor attachment through binder jetting.

Bennett et al. [136] conducted a life cycle and environmental performance analysis of directed energy deposition and welding operation for the repair of a casting die. The outcome of the study shows a 12% reduction in CO_2 emissions when using AM, compared to the traditional welding operation. Priarone et al. [137] investigated the energy and carbon-saving potential of wire arc additive manufacturing for the repair of mold inserts and found that energy consumption and CO_2 emissions could potentially be decreased by 26% and 32%, respectively.

Secondly, AM allows the recycling of polymer-based products [44]. However, the recyclability potential of various AM materials differs [138]. Faludi et al. [139] stated that some unused metallic powder during the AM process can be used for the same application up to eight times after sieving, though with lower quality each time. However, Daraban et al. [140] indicated that the repeated recovery and reuse of AM materials is not applicable to all materials, for instance, titanium and aluminum alloys, due to reactivity with environment conditions. This may result in a loss of approximately 20% to 25% of the recycled metal powder in the process.

Walachowicz et al. [141] conducted a comparative analysis of the lifecycle of the industrial repair process of gas turbine burners using traditional machining and additive manufacturing, specifically selective laser melting (SLM), with an emphasis on the energy, resource and recycling analyses. The results show a potential for reduction in the depletion of abiotic resources by 50% for the SLM and 83% for traditional machining during recycling. The authors further indicated that it is difficult to achieve a reduction in costs and material losses in metal powder production. Thus, the metal powder production process is less cost effective both in installation and operation as frequent waste treatment is required before disposal. On the contrary, with wire-based metal additive manufacturing, a higher feedstock efficiency within the range of 93–98% could be achieved with the potential of reducing the overall waste generated during AM by approximately 30% [142,143].

Recycling helps to reduce the quantity of polymer waste in landfills and marine habitats [103]. Some of the polymer materials used are biodegradable; hence, they do not degrade the environment at their end-of-life state [100]. Thirdly, AM can be used to make products on demand. Products can be kept in the form of digital inventory and produced only when necessary [115]. As a result, the environmental burden associated with overproduction and keeping physical inventory is eliminated. Another benefit of on-demand manufacturing is that it is localized; hence, it eliminates the negative environmental impact of transportation.

Additive manufacturing can reduce waste in the manufacturing process in several ways, thus contributing towards lean manufacturing. One major contribution is reducing the supply chain lead time through direct conversion of digital models to physical [129]. This helps to eliminate several production steps associated with conventional manufacturing [144]. As a result, the overall operational efficiency in manufacturing products is improved. The digitalized manufacturing system employed in AM eliminates human errors associated with traditional production methods, thereby improving quality [1]. Another contribution of the digitalized systems is that it allows products to be stored in the form of digital files as opposed to physical inventory [115]. Digital files can be printed locally and on demand. Accordingly, the costs associated with keeping unnecessary physical inventory are eliminated. Overproduction can be avoided since products can only be produced when required. The localized production opportunity offered by AM reduces the waiting time associated with outsourcing products from elsewhere [116]. AM can produce products with optimized designs that perform better than their conventional counterparts. The freedom of design offered by AM provides the opportunity to make products with improved quality and durability [108].

Some of the studies in the literature focused on the production of AM-based injection molding and forming tools [112,113]. The usage of such tools has led to a reduction in the overall cycle time and improved quality. The AM technology can promote green, lean and sustainable manufacturing with the potential for reducing environmental degradation and material usage. Although existing studies differ in the amount of energy consumed during the AM vis-à-vis conventional manufacturing, the environmental friendliness and reduction in carbon footprints exceed those in the conventional manufacturing process. AM provides a feasible option for producing complex parts with improved geometry with the tendency for weight reduction and considerable energy savings. Thus, the energy saved using lightweight materials can compensate for the energy required for the AM main processes and post-processing. Evidence from exiting works indicated that the positive or negative impacts of the AM processes on the environment vary with AM processes employed. For instance, electron beam melting (EBM), selective laser melting (SLM) and selective laser sintering (SLS) can contribute positively to the environment through improvement in design to reduce the total energy consumption and recycling of materials. However, extra energy may be consumed during material processing and the raw material consumed, such as in the form of gases, compressed air, argon, and nitrogen, which may increase the production cost and contribute to marine, terrestrial and freshwater toxicity [66,67,145–147]. For AM processes such as stereolithography (SLA), the energy consumption due to post-processing is relatively low compared to others and the process residues are also negligible, making the post-processing process more environmentally friendly. However, the preprocessing stage is highly energy intensive. For fused deposition modelling (FDM), the raw material consumption is low and provides the option of material recycling. The generated process residues are usually negligible. However, the main processing stage is energy intensive and may contribute to freshwater and marine eutrophication [148].

Existing studies found that the evolution of AM technology has positive impact on the economic, social and environmental factors of sustainability and the industrial revolution [149,150]. For instance, it creates employment opportunities [151,152], enhances lightweight development of components for the transport sector to achieve energy efficiency and reduction in emission generation [153,154], assists organizations to achieve their lean and green strategy [155], enhances materials development for special biomedical applications, [156], improves the overall organization's value chain [157,158].

5. Conclusions, Recommendations and Future Works

This study aimed to examine the progress made in the development of additive manufacturing technology to support lean and green manufacturing. This was achieved with the use of the PRISMA approach. The systematic literature review was conducted on 158 articles that met the selection criteria. The outcome of the study indicated that additive manufacturing is more robust when compared to the conventional manufacturing technique and can be used to achieve waste reduction, reduction in emission generation, and carbon footprints with significant energy and material conservation. The findings also indicated that the additive manufacturing process also boasts time- and cost-effectiveness during manufacturing compared to the conventional manufacturing technique. However, some of its limitations include the following: selection of the appropriate build speed, product development at high resolution, biodegradability of some AM materials, biocompatibility and mechanical properties of fabricated parts, the need for postprocessing for some parts, and the composition of multi-material parts, amongst others. Although the process is energy intensive, the careful selection of the suitable additive manufacturing process to be employed based on the requirements coupled with a proper product design may result in considerable energy savings at the preprocessing, processing or postprocessing stages. Furthermore, effective process design and optimization as well as proper selection of the right material that suits an intended application are necessary to optimally harness the benefits of AM.

Products manufactured with AM technology are usually lighter in weight with less material and energy consumption as well as less waste generation. This aligns the principles of green manufacturing, which focus on reducing the negative environmental impacts caused by manufacturing processes. The technology allows for a simpler, shorter and effective value chain, ensuring quick product manufacturing and part replacement compared to the conventional manufacturing techniques. It allows the use of recycled materials and gives room for product localization, thereby eliminating the economic and environmental effects of logistics and complex value chains. Sustainability can be achieved via the implementation of AM by implementing just-in-time production to reduce inventory waste. The automation of the software used for direct product manufacturing increases the precision and accuracy of parts produced, thereby reducing waste and improving product quality in line with the principle of lean manufacturing. All these benefits of AM ensure that the manufacturing process is cost-effective and environmentally sustainable. Sustainable product development ensures that the manufacturing operation is conducted in a time- and cost-effective manner with less environmental impact. Therefore, the outcome of this study indicates that there is a link among AM, green and lean manufacturing in order to achieve sustainable manufacturing goals.

This study provides empirical, conceptual and theoretical findings that can assist manufacturing organizations in their quest to minimize waste generation and achieve material energy efficiency throughout product lifecycles. The study also adds to the understanding of additive manufacturing and contributes to the exiting literature on the impact of additive manufacturing on lean, green and sustainable manufacturing. The synthesis of the literature presented in this study can help manufacturing industries achieve sustainability in terms of resources, cost and environmental conservation. It is recommended that manufacturers adjust their business models to incorporate additive manufacturing, especially for developing complex and spare parts. As the world gradually leans towards a safe and sustainable manufacturing process, a gradual shift to alternatives such as AM may assist manufacturing organizations in the development of more environmentally friendly products with increased value-added activities in a time- and cost-effective manner. This study is limited to the investigation of the relationship among AM, LM and GM. Future works could consider the comparative analysis of the life cycle assessment of the additive and conventional manufacturing techniques in order to quantify the energy requirements for specific products.

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