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Green manufacturing in the age of smart technology: A comprehensive review of sustainable practices and digital innovations

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Abstract

The paper examines how smart technologies like the Internet of Things (IoT), big data, and artificial intelligence (AI) can be leveraged in the manufacturing industry to enhance sustainability. It points to Industry 4.0 and the role of digital technologies in developing smart factories, optimizing resource usage, and eliminating waste. This review highlights the industry's shortcomings, such as initial investment and skills shortage that will derail the use of these technologies. Additionally, it alleviates data security concerns as we become more reliant on IoT devices. The paper also features instances of organizations such as S.C. Johnson and Dell, which are demonstrating leadership in sustainable practices and digital innovations such as recycling and energy-efficient product designs. Overall, the review highlights smart technologies' ability to enable green manufacturing, which will help make the manufacturing sector a better place in the future.

Keywords: Green Manufacturing, Smart Technology, Sustainability, Digital Innovations, Industry 4.0

1. Introduction

In green manufacturing, which encompasses environmentally friendly processes to minimize emissions and energy consumption, industries around the world are increasingly concerned. This has become much more advanced with the use of smart technology, incorporating digital solutions to automate the manufacturing process while keeping the environment in mind. Smart technologies such as IoT, big data, and AI have changed the world of manufacturing, providing possibilities to re-use resources efficiently and reduce waste for sustainability [1, 2].

Industry 4.0, as it has come to be called, places the emphasis on the use of digital technology and green in manufacturing processes in recent years. It involves smart factories that use connected machines and data in real time to optimize and be more sensitive to environmental issues. These improvements help to make supply chains more transparent, predictive maintenance easier, and circular economy concepts, like reusing materials and reducing waste, will be widely adopted [3, 4].

Adding digital tools to green manufacturing not only contributes to regulatory compliance and sustainability, but it also benefits financially. Businesses that use these technologies will also save substantial costs by increasing the efficiency of processes, reducing energy use, and minimizing waste. Moreover, as consumers grow more eco-friendly, companies that adopt sustainable solutions through smart technologies can further increase market share by enhancing brand value and loyalty [5, 6].

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This in-depth review examines some of the sustainable practices that are integrated into green manufacturing and how digital technologies play a critical role in this change. Examining the emerging trends, problems, and case studies, the study will offer practical insights on how industries can adopt smart technologies to realize sustainable manufacturing targets that are thereby contributing towards planetary targets of conservation and sustainable development. The findings will be useful for practitioners, policymakers, and researchers who wish to make sense of the dynamic between industry practices and technological change in sustainability [7, 8].

2. Methodologies for Implementing Green Manufacturing

- *Adoption of Additive Manufacturing (AM) Technologies*: AM, or 3D printing, is sustainable, as there is less waste during the process. Material consumption can be optimized, and materials recycling in the circular economy model helps with sustainability [9].
- *Integration of Cyber-Physical Systems (CPS) and Industry 4.0*: With CPS, the energy savings in manufacturing are tremendous. Industry 4.0, like IoT, AI, and big data analytics, could improve process efficiency, track energy usage in real time, and enable data-based decision-making to eliminate energy waste [10].
- *Implementation of Smart Services*: Smart services consist of automating and digitizing the operations to maximize performance and conserve energy. The proof is in the pudding that smart services create sustainable transformations and improve overall performance in manufacturing companies [11].
- *Application of Lean Manufacturing Principles*: Lean manufacturing is about minimizing waste in order to increase productivity. If used in combination with green strategies, a lean approach can also be used to maximize material and resource efficiency. Investing in process improvements will save energy and leave a smaller carbon footprint [12].
- *Use of Renewable Energy Sources*: In the case of manufacturing, shifting to renewable energy (solar or wind) could make it much less carbon intensive. One can do this with smart energy management devices that can automatically adjust energy use to data and demand [10].
- *Implementation of Sustainable Supply Chain Management*: A sustainable supply chain is an effort to make sustainability-based decisions at every step of the production process. This means choosing suppliers who are environmentally conscious and using green logistics to reduce transportation emissions [9].
- *Training and Competency Development*: Training and capacity-building in the workforce are necessary for the organization to be sustainable. Green technologies and practices can be taught to the workforce to make them more skilled in implementing sustainable strategies [13].

3. Framework for Integrating Sustainable Practices with Digital Innovations in Green Manufacturing

For green manufacturing in the age of smart technologies, companies need to adopt a model that bridges the gap between sustainable and digital. These are the steps that provide a methodology:

- *Step 1, Assess Current Manufacturing Practices*: This can be done by assessing the entire manufacturing processes of the organizations. These include determining where energy consumption, waste generation, and resource use can be reduced. Data analytics can be utilized to identify manufacturing inefficiencies and optimizations [14].
- *Step 2, Set Clear Sustainability Goals*: It’s important to define clear sustainability objectives. These could include reductions in carbon emissions, waste reduction, and resource efficiency. Defining the goals helps guide the implementation plan and tracking achievement. It also increases credibility by aligning objectives with the standards and laws in the industry [15].
- *Step 3, Adopt Innovative Technologies*: It’s vital to invest in smart technologies to move to green manufacturing. By using IoT devices, production can be monitored on the same day, allowing manufacturers to change production processes automatically to minimize waste and maximize energy savings. Further, advanced manufacturing processes like AM can reduce material waste [14].
- *Step 4, Integrate Renewable Energy Sources*: Implementing renewable sources of energy, like solar or wind, into manufacturing can drastically reduce fossil fuel usage. Business owners must review their

energy requirements and look at installing renewable energy on-site or purchasing green energy from suppliers.

- *Step 5, Enhance Supply Chain Sustainability*: The supply chain must be more sustainable. Supplier sustainability indicators can help companies find those that reduce their environmental impact. Further, efficient logistics and transportation will reduce emissions in materials procurement and product flow [15].
- *Step 6, Foster Employee Engagement and Training*: To succeed, it's important to involve employees in sustainability. Training in sustainable manufacturing and the adoption of new technologies contribute to a culture of sustainability in employees. This can be equally effective in getting employee ideas and changes.
- *Step 7, Monitor and Report Progress*: Monitoring and reporting on sustainability data on a regular basis is crucial to understanding how green manufacturing programs are working. Digital dashboards and analytics software can help track journeys and results in terms of goals. Clear reporting increases accountability and also builds stakeholder confidence.
- *Step 8, Continuously Improve and Innovate*: Green manufacturing is an art that needs to be kept getting better and better. Companies should regularly assess their sustainability performance and research new technologies and techniques to improve efficiency and sustainability. Information on current trends and innovations in sustainability can offer competitive advantages [14].

4. Applications of Sustainable Manufacturing Practices in Industry 4.0

4.1. Overview of Industry 4.0

Industry 4.0 is the fourth industrial revolution, where digital technology, including the IoT, AI, and big data analysis, is integrated into manufacturing. This revolution will establish smart factories with integrated networks and real-time data to optimize production and become more sustainable [16].

4.2. Sustainable Manufacturing Practices

Sustainable production seeks to produce products and services that cause as little environmental harm as possible and provide the most social and economic benefits. These include encouraging resource efficiency, waste minimization, and energy savings [17]. These practices comply with the United Nations Sustainable Development Goals (SDGs) by encouraging ethical consumption and production practices.

4.3. Applications of Sustainable Manufacturing Practices

- *Resource Efficiency*: Industry 4.0 technology enables manufacturers to better use the resources. Advanced IoT sensors, for example, can also monitor consumption in real time to identify areas where efficiencies can be enhanced [17]. This is very important in industries like the textile and apparel industry, which suffers from waste.
- *Waste Reduction*: Intelligent manufacturing makes it simple to reduce waste with predictive maintenance and lean production methods. Using AI and machine learning algorithms, companies can detect equipment failures in advance and schedule proper maintenance to avoid unplanned downtimes and waste due to production disruption [18].
- *Energy Management*: Industry 4.0 will use clean power and smart energy management. These systems monitor energy usage and optimize energy consumption, which plays a vital role in sustainable development. For instance, combining solar panels and IoT appliances allows factories to monitor energy usage better.
- *Supply Chain Transparency*: Blockchain technology is becoming a leading tool in order to make supply chain transparent and sustainable manufacturing possible. Blockchain offers a safe and open way to track materials and products, thus eliminating fraud and encouraging more responsible sourcing [19]. This is especially true in sectors such as food and clothing, where customers are demanding more detail on the production source.

- *Adoption of AM*: 3D printers enable companies to manufacture items at a moment's notice, which saves material in subtractive manufacturing. In addition, 3D printing allows biodegradable and recycled materials, which are crucial to the circular economy [20].
- *Circular Economy Integration*: The circular economy, which involves reuse and recycling, can also be supported by Industry 4.0 solutions. Smart manufacturing processes also enable materials to be reclaimed from end-of-life products and integrated back into production [21]. This regenerative model not only reduces waste but also ensures sustainability.

5. Digital Innovations Driving Green Manufacturing

5.1. The Role of Digital Innovations

Digital innovations refer to technologies that help turn traditional manufacturing into more sustainable forms. Key technologies include:

- *IoT*: IOT gadgets provide continuous monitoring and data collection during the manufacturing process. This ability leads to better resource management, preventative maintenance, and more flexible production times [22].
- *AI*: AI algorithms can process a large amount of data, simplifying manufacturing processes and making smarter decisions. It leads to less material waste and energy consumption, meeting the objectives of green manufacturing [23].
- *Digital Twins*: A digital twin is a computer-based replica of an actual physical property or process. Through simulation, manufacturers are able to find inefficiencies and make changes without interrupting real-world processes. It is a technology that improves outcome prediction and minimizes waste [24].
- *Automation and Robotics*: Automation solutions simplify the manufacturing process, which can increase the process efficiency and labor savings. Robotic systems in combination with IoT and AI can streamline operations to reduce consumption and recycling costs [25].

5.2. Benefits of Digital Innovations for Green Manufacturing

Digital innovations have many advantages for green manufacturing:

- *Enhanced Efficiency*: Digitally changed processes ensure optimal use of resources and less waste. AI-based analytics are also useful for adjusting production parameters to prevent waste material [26].
- *Sustainability Reporting*: Digital tools help in the measurement of sustainability indicators and the environmental footprints, helping organizations to disclose their carbon footprints and resource use accurately. This openness leads to accountability and continuous improvement in sustainable practices [27].
- *Circular Economy Promotion*: The digital tools advance circular economy by allowing repurposed materials to be put back into production. Lean manufacturing methods combined with digital tools help reduce and reuse waste [28].

5.3. Challenges and Future Directions

- *Initial Investment*: Implementation of cutting-edge digital technologies usually requires a high upfront investment, making it difficult for smaller companies [26].
- *Skills Gap*: These digital technologies require skilled workers to apply and control them. That skill asymmetry may hinder the use of new technologies [22].
- *Data Security*: As the number of IoT devices and data analytics continues to grow, data security and privacy concerns have also grown, requiring stronger cybersecurity protocols [29].

6. Green and Smart: Leading Companies Pioneering Sustainable Manufacturing Practices with Smart Technologies

Green manufacturing, coupled with smart technology, has encouraged organizations to adopt green strategies and technology to streamline their manufacturing. Here are ten companies that are best at this field.

6.1. Dell

Dell embodies recycling and the circular economy at the cutting edge of technology.

- *Sustainable Practices*: Dell has committed to using recycled or renewable materials for all of its packaging and 50% of its products by 2030 [30]. The company also makes use of recycled plastics and metals, including post-consumer recycled materials, in their products [31].
- *Digital Innovations*: Dell partnered with Intel to create "Concept Luna," a proof of concept for environmentally friendly PC design focused on increasing component availability, reuse, and recycling in order to minimize waste and emissions. Further, their energy-efficient products powered by Intel processors are designed to ensure the data center runs at its best and will minimize the impact on the environment [32].

6.2. Hewlett-Packard (HP)

HP has become one of the leaders in sustainability in manufacturing.

- *Sustainable Practices*: HP addresses climate issues by taking active measures to reduce waste, such as utilizing ocean-bound plastics in its products. In 2019, HP recycled more than 875 million ink and toner cartridges, a significant increase in its sustainability [30].
- *Digital Innovations*: Sustainability-oriented print innovations from the company enhance printing efficiency by leveraging recycled materials that directly contribute to lower environmental impact [33]. HP's cutting-edge technology helps make the products circular and sustainable.

6.3. Honda

Honda has led its sustainability effort by building in renewable energy and significantly reducing carbon emissions.

- *Sustainable Practices*: Honda's "Green Path" plan strives to minimize resources and noxious materials and has already announced its goal to have all plants carbon-neutral by 2050. Honda operates wind turbines in their Ohio plant that provide significant electricity and cut CO_2 emissions by more than 60% via rail transport for vehicle distribution.
- *Digital Innovations*: It also is making investments in hybrid and electric vehicles (EVs) and demonstrating manufacturing innovations that are environmentally friendly [30].

6.4. S.C. Johnson

Zero waste is evidence of S.C. Johnson's dedication to sustainable manufacturing.

- *Sustainable Practices*: The company achieved zero waste to landfill in all of its sites worldwide before the 2021 date, fundamentally reshaping waste operations. Also, S.C. Johnson promotes responsible sourcing and sustainable materials in its products.
- *Digital Innovations*: With its Greenlist process, S.C. Johnson assesses the environmental footprint of product ingredients, allowing them to reformulate their products in ways that increase sustainability [30].

6.5. Hitachi

Hitachi's example reflects both sustainability and innovation.

- *Sustainable Practices*: Hitachi, which aims to be carbon-neutral by 2030, adopts clean technology and eco-friendly practices in all areas of its manufacturing processes. Their solutions optimize energy efficiency and monitor ecological impacts with ease.
- *Digital Innovations*: Through cutting-edge data analytics and machine learning, Hitachi's Lumada Manufacturing Insights helps organizations build data-driven businesses that improve supply chain efficiencies and sustainability [34].

6.6. Tesla

Tesla is also famous for its sustainability practices when it comes to EV manufacturing and renewable energy products.

- *Sustainable Practices*: The company has an ambitious goal to make all its factories carbon neutral and has done some pretty good things, like relying on the sun and implementing battery recycling. The production at Tesla is designed for low waste and emissions, and they strive to recycle 100 percent of battery manufacturing scrap.
- *Digital Innovations*: Tesla uses AI and robotics for optimal manufacturing. This is made possible through big data analytics in real-time monitoring and customization in production for better efficiency and reduced waste [35].

6.7. Procter & Gamble (P&G)

P&G is one of the only consumer product manufacturers to be committed to its efforts to be as green as possible.

- *Sustainable Practices*: The company aspires to operate at 100% renewable energy and is on track for zero waste in landfills at its manufacturing facilities. And P&G is also into sustainable and recycled-based packaging.
- *Digital Innovations*: P&G is also using digital technologies like AI and IoT to help improve supply chain performance, product lifecycle management, tracking resource consumption, and sustainability indicators [36, 37].

6.8. IBM

IBM's approach to technology and sustainability is geared towards environmental and operational efficiency.

- *Sustainable Practices*: IBM is committed to net-zero emissions by 2030 and energy from renewable sources in its operations. It promotes a circular economy and creates reuse-and-recycle products [38, 39].
- *Digital Innovations*: AI and data analytics are used by the company to provide companies with tools to optimize sustainability reports and manage the use of resources. The digital ecosystems from IBM enable customers to scale their processes for sustainable business objectives [40, 41].

6.9. Patagonia

Patagonia is a sustainable fashion and outdoor brand with an eye to the green.

- *Sustainable Practices*: Recycling and reusing are key processes followed by the company while manufacturing. Patagonia uses organic cotton and recycled polyester and has effective waste reduction strategies across the product lifecycle [42, 43].
- *Digital Innovations*: They also use digital to increase the transparency in their supply chain so that customers can understand the sustainability of what they are buying. Patagonia has also gone digital and optimized customer experience for more environmental commitment [44, 45].

6.10. Siemens

Siemens demonstrates the whole package by deploying smart technology in manufacturing.

- *Sustainable Practices*: Siemens targets carbon-neutral operations around the world by 2030. The company has energy-efficient and renewable energy technologies for its production plant that make the facility substantially less carbon-based [46].
- *Digital Innovations*: Siemens is utilizing digital twins and modeling software for more efficient production and energy management. Their solutions allow companies to model production processes and thus minimize waste and optimize resources [47].

7. Literature Review of Green Manufacturing through Smart Technology Integration

The number of articles covered for green manufacturing through smart technology integration are shown in Figure 1 from 2015 through 2024.

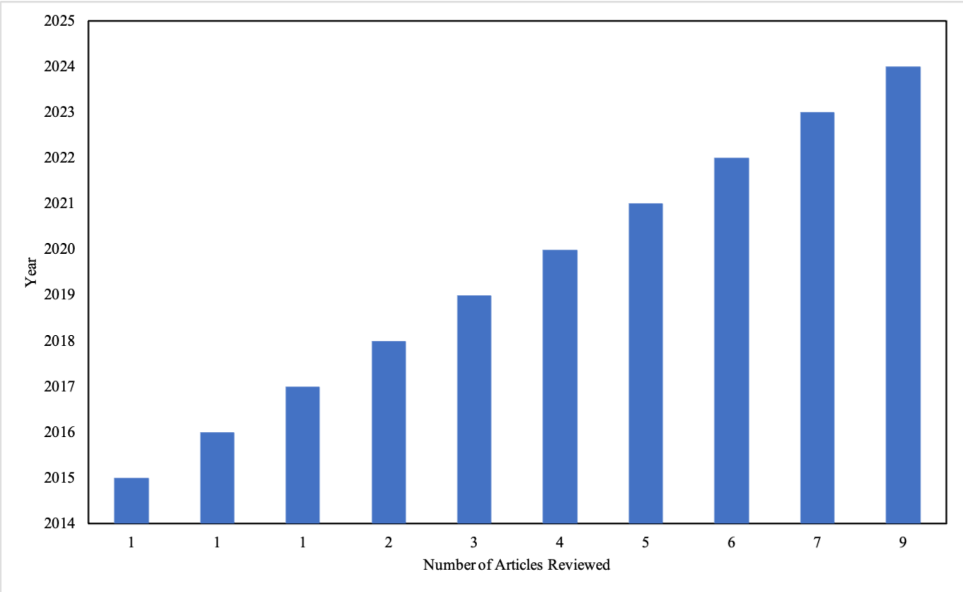

Fig. 1. Articles reviewed (2015-2024) for green manufacturing through smart technology integration

Table 1 below presents a quantitative distribution by publisher of the number of articles related to green manufacturing through smart technology integration, along with their indexing details.

Table 1. Number of articles from different publishers reviewed for green manufacturing through smart technology integration, along with the indexing details of all these publishers

Publisher	Indexing	Number of Articles Reviewed
MDPI	Scopus, Web of Science, PMC, PubMed, MEDLINE, DOAJ, Engineering Village, CAS, FSTA, BibCnrs, CNKI, CNPIEC, dblp Computer Science Bibliography, Dimensions, EBSCO, ANVUR, JCR, Norwegian Register for Scientific Journals, Series and Publishers, and SCImago Journal & Country Rank, EZB, JournalGuide, and Research4Life, Google Scholar, Scilit, and WorldCat	6
IEEE	Scopus, Web of Science, ProQuest, IET, NLM, CrossRef	5
Springer	ADS, DOAJ, DOAB, EconLit, EI Compendex, GeoRef, Google Scholar, IET Inspec, MathSciNet®, MEDLINE, PsycINFO, Psyndex, PubMed Central, RePEc, SciFinder® and STN, Scopus, Web of Science, zbMATH	5

Elsevier	DOAJ, Web of Science, Scopus, PubMed Central, MEDLINE	4
Taylor & Francis	Scopus, PubMed, JCR, Google Scholar	3
EDP Sciences	Crossref, ESCI, DOAB, OAPEN, Scopus	2
American Institute of Chemical Engineers Journals	Scopus, Web of Science (SCIE), CAS	1
Association for Computing Machinery	AI2 Semantic Scholar, AMS MathSciNet, Baidu, Clarivate / ISI (JCR, SCI, SCIE), CNKI, DBLP, DeepDyve, DTU, EBSCO (EDS, HOST, EI Compendex), Elsevier (SciMago, SCOPUS), EPO, ExLibris Google Scholar, IEEE (Xplore), IET Inspec, iGroup, Meta - Chan Zuckerberg Initiative, Microsoft Academic Search, NII, OCUL Scholars Portal, Odysci, OhioLink, Pathgather, ProQuest: Summon® Service, SIPX, SUWECO, WorldCat, WTI, Yewno, zbMATH	1
China Engineering Science Press	EI Compendex, Scopus, CSCD, CNKI	1
Darcy & Roy Press	Google Scholar, J-Gate, Scilit, Crossref, ResearchGate, CLOCKSS, SemanticScholar, LOCKSS PKP	1
Emerald	ALMA, EBSCO EDS, Primo, Summon, WorldCAT	1
Frontiers	PubMed Central, DOAJ, Google Scholar, Chemical Abstracts Service, EBSCO Information Services, IET Inspec, MedLine, OpenAIRE, Polska Bibliogafia Naukowa, PsychINFO	1
IIP Series	RSquareL, Amazon, Google Books, IIP Digital Library	1
Inderscience	Scopus, Academic OneFile (Gale), Compendex, Web of Science (ESCI)	1
IOP Publishing	Web of Science, Scopus, ReadCube, CPCI-S, Clarivate, CABI, CNKI	1
Penerbit UTM Press	SCOPUS, ESCI-WOS, ACI, MYCITE, MYJURNAL	1
Science Proceedings Series	Web of Science, Scopus	1
Sciendo	Web of Science (ESCI), Scopus, DOAJ, ERIH PLUS	1
SPIE	Web of Science, Scopus, PubMed, Astrophysics Data System, Chemical Abstracts, Ei Compendex, Inspec, International Aerospace Abstracts, Index to Scientific & Technical Proceedings, Physics Abstracts, SPIN, MyScienceWork	1
UIKTEN	Web of Science (ESCI), Scopus	1
Total		**39**

Taib et al. (2015) focused on green management (GM) and technology (GT) in Malaysia's electrical and electronics production and how these practices, taken together, contributed to business sustainability by dealing with environmental challenges. They used a questionnaire survey of the industry members and found that GM and GT practices positively correlated with business sustainability, underscoring the environmental and operational advantages of bundled green [48]. Meanwhile, Peng et al. (2016) examined how green manufacturing technology spread in China (e.g., via the introduction of high-efficiency motors (HEMs) through disruptive policies such as subsidies and energy performance contracts) in particular in Dongguan City. This research outlined key impediments to GT adoption (such as lack of finance and policy) and found the power of targeted incentives to create a supportive climate for energy savings [49]. Badarinath and Prabhu (2017) wrote about how the IoT could play a key role in green manufacturing, especially energy efficient processes and resource efficiency made possible by smart technologies such as wireless sensor networks and big data analytics. Their study recommended four-layer service-oriented architecture (SOA) for IoT adoption in manufacturing, such as predictive maintenance and shop floor automation [50].

Yadav (2018) was interested in "smart nature agriculture," which combined science with a view to minimize greenhouse gas emissions and improve yields by precision planting, zero-weeding, and irrigation. These results showed robust productivity gains (572 quintals per hectare) and decreased greenhouse gas emissions, with the method being generalizable to many climates and soil types [51]. On the contrary, Azeez and Akinlabi (2018) investigated friction stir welding (FSW) as a green manufacturing technology. The research they did focused on improving welding settings, including speed and input heat, to improve joint reliability and efficiency. A closed energy system was recommended to minimize waste, and, when it came to joint reliability, lower heat input was associated with higher joint reliability [52]. Ignatov and Subkhankulov (2019) have proposed an eco-friendly manufacturing process for multilayer polymer composites used in products such as wind turbine blades. They tested hot air pressure for product porosity, controlling it to 0.72% and lowering energy consumption with higher-quality products and fewer toxic materials exposed to workers [53].

Steger-Jensen et al. (2019) applied Advanced Planning and Scheduling (APS) technology in the manufacturing workflow to account for the environmental inputs for resource allocation, such as machine allocation and energy consumption. Their studies used simulation models in Danish process factories to optimize waste, emissions, and energy use, focusing on the utility of human choice in managing complex production factors [54]. Terouzi and Oussama (2019), by contrast, studied quality control of agro-food smart factories with Attenuated Total Reflectance-Fourier Transform Mid Infrared Spectroscopy (ATR-FTMIR) and multivariate analysis. This approach made product testing efficient, reliable, and cost-effective, specifically enhancing sustainability by ensuring high standards of quality control within a streamlined process [55]. Zhang et al. (2020) smart knowledge application approach with design matrix for mapping design steps and knowledge needs at product lifecycle for waste circuit board recycling. It was a method that used machine learning to marry design processes with knowledge-based practices and supported green manufacturing by knowledge-based, systematized processes [56].

García-Muiña et al. (2020) based Industry 4.0 innovations in a ceramic tile manufacturer in Italy by studying sustainability across the environmental, economic, and social pillars using the Triple-Layered Business Model Canvas. They showed more sustainability through measures such as less environmental footprint, cost-efficiency, and community involvement [57]. On the other hand, Samad and Bienert's paper (2020) on the energy efficiency of manufacturing via smart grids, considered direct load control, automated demand response, and microgrids as approaches to increasing energy efficiency and renewable energy. Communication and control issues were discovered by their research to be a barrier to mass smart grid adoption in manufacturing over residential and commercial markets [58]. In the meantime, Buba and Ibrahim (2020) analyzed the intentions of Nigerian manufacturers to use Green IT, applying the Theory of Planned Behavior and Norm Activation Theory to simulation decision-making. Their results pointed to managerial attitude and regulatory pressure as prime drivers of Green IT in order to avoid destroying the planet with green technologies [59].

Calì's work (2021) in "Smart Manufacturing Technology" analyzed digitization of manufacturing in all sectors and its incorporation of digital systems for productivity and autonomous processes. Sustainability was the focus of the study, with experimental findings showing cost savings and resource conservation in production [60]. Meanwhile, Plank et al. (2021) explored a general IT-system architecture specifically tailored to green manufacturing through real-time monitoring, decision-making, and waste management by way of Industry 4.0 concepts. Various case studies in the study described how this architecture can enable more efficient operations and a greener environment in industrial applications [61]. Hakola et al. (2021) studied roll-to-roll (R2R) printing for multi-layer smart labels in recycled paper. Their study provided a sustainable electronic label that was highly successful for readability and durability over many cycles and represents electronics sustainability through e-waste minimization [62].

Fraga-Lamas et al. (2021) investigated how Green IoT (G-IOT) and Edge AI could be used to drive an environmentally friendly digital transformation in Industry 5.0 and how they could reduce carbon footprints and improve productivity even as AI-led integration generates increased energy use. Their paper included a demonstration application and smart workshop using mist computing, highlighting the use case of G-IoT and Edge AI to drive a circular economy and identifying rules for IOT development that are sustainable [63]. Molina et al. (2021) went further, with the emphasis on how new technologies are changing the world of sustainable manufacturing. Their studies focused on maximizing productivity and resource use (mainly energy and water) at the expense of emissions. One of the major findings was the importance of taming process variables like temperature and friction for optimal performance and green manufacturing [64]. Li and Han (2022) presented an industrial roadmap for green manufacturing by constructing a green innovation network based on big data and AI. Their roadmap merged four smart modules—development, production, operation, and service—to improve the efficiency of production and reduce environmental footprint, while putting the importance on data-driven innovation as the way forward for sustainable economic growth [65].

Gevorkyan et al. (2022) focused on energy-efficient sintering technology for ceramic filters in multi-floor manufacturing complexes in cities to save energy and increase productivity. They reported that using certain additives decreased sintering temperatures by 20%, reduced the thermal cycle by 19%, and saved up to 40% of electricity, offering a useful energy efficiency model for ceramic filter production [66]. By contrast, Chi (2022) focused on integrated circuit (IC) technologies and systems with a focus on low-power, modular IC designs for green manufacturing. His research examined how automation, robotics, and waste treatment can be deployed in smart manufacturing in the energy, automotive, and smart city industries to achieve sustainability through reduced carbon emissions and efficient use of resources [67]. Kim et al. (2022), to assist small and medium manufacturers in smart manufacturing, developed the Smart Connected Worker Edge Platform. Combining IoT and low-cost computing hardware, their platform facilitated data-driven decision-making at the factory edge, driving higher productivity and sustainability. They found that it could be economically feasible to use cost-effective smart manufacturing tools to increase efficiency and promote sustainability within small-scale production lines [68].

The study by Wu et al. (2022) on Sustainable Food Smart Manufacturing Technology (SFIMT) focused on the challenges faced by the food processing industry and greener manufacturing. Their work created a model for sustainable technology evaluation and prioritized innovations that improve sustainability and satisfy consumer needs for nutritious food. The most significant outcome was to identify a range of promising technologies that would enable food production to become sustainable [69]. Dey et al. (2022) on carbon emissions and waste elimination in a manufacturing-remanufacturing process through green technologies and automated inspection. Their studies showed that it had reduced carbon emissions by 2.81% and waste by 2.37%, along with a production cost reduction of 18.26%. The study concluded that these technologies can not only make manufacturing processes more environmentally sustainable but also economically efficient [70]. Han et al. (2023) considered Environmental, Social, and Governance (ESG), environmentally, socially, and governance-sensitive GT innovations in manufacturing. They discovered the significance of embracing renewable energy, circular economy, and data-driven technologies such as AI and data analytics. These practices optimized the use of resources, energy, and waste removal to promote sustainable manufacturing [71].

Gibson's study (2023) on shortening the supply chain with smart manufacturing and GT highlighted the need to leverage an IoT platform to overcome supply chain inefficiencies, better coordination, and sustainability. These results showed the potential of IoT to minimize waste and optimize the use of resources, with a special focus on environmental sustainability [72]. Leong et al. (2023) focused on smart manufacturing technology (SMT) to meet the ESG sustainability targets. They demonstrated that SMT could be used for data-driven decision-making and process optimization, helping to reduce the footprint, wages, and governance issues. Although the research recognized obstacles to SMT adoption, it also emphasized that such obstacles could be overcome for long-term viability and competitive advantages [73]. Deja et al. (2023) focused on AM in smart city multifloor manufacturing clusters (CMFMCs), which addressed its sustainability aspects for production waste minimization and material reuse. Their studies resulted in a new facility layout model for CMFMCs, which optimizes the spatial placement of AM equipment to increase efficiency and sustainability in urban manufacturing. They also provided management solutions for balancing resources to ensure efficient megacity operation [74].

Shen and Zhang (2023) addressed the fusion of intelligent manufacturing and green technologies for pollution reduction. Their work using questionnaires and data from manufacturing companies proved that intelligent manufacturing methods boost efficiency, reduce waste and emissions, and have better ecological footprints [75]. Conversely, Zhu et al. (2023) assessed the effects of the digital economy on green development in manufacturing, especially in the "Belt and Road" countries. Using panel data analysis, they concluded that the digital economy increased Green Total Factor Productivity (GTFP), but with a slow impact and thresholds of human capital and trade competitiveness required for it to deliver the full benefits [76]. Aminzadeh et al. (2023) discussed the use of Industry 4.0, including smart laser welding to ensure sustainability in manufacturing. Their work highlighted the potential of IoT, big data, and continuous monitoring to improve welding, minimize defects, and foster sustainable production [77].

Agarwal et al. (2024) prioritized the barriers to adopting green smart manufacturing (GSM) in the Indian automobile sector through the Analytical Hierarchy Process (AHP). The study identified financial inefficiencies, insufficient dedicated suppliers, and poor top-level leadership as the primary barriers to the implementation of GSM and a multi-layered strategy to tackle these bottlenecks and enable sustainable manufacturing under Industry 4.0 [78]. Zhang et al. (2024) examined the link between smart product platforms and GT development in automotive manufacturing. From a representative sample of 1,240 Chinese car firms, the paper reported that smart product platforms supported GT innovation, and corporate innovation input served as a full-blown facilitator. Furthermore, companies' level of intelligentization balanced this correlation, suggesting that enlightened smart technologies would enable sustainable innovation and NetZero emissions [79]. Li et al. (2024) analyzed digital technology's contribution to carbon performance through green innovation in manufacturing companies. The research, which analyzed data from Chinese manufacturing companies, concluded that digital technologies significantly improved carbon performance, with green innovation acting as an intermediate factor. Moreover, the paper argued for the use of environmental information disclosure to boost the efficiency of digital tools for carbon reduction [80].

Liu et al. (2024) used Building Information Modeling (BIM) and intelligent tooling to help them develop smart manufacturing technologies for reinforcing bars for bridge precast concrete construction projects to improve productivity and control of steel fabrication, significantly improving infrastructure disaster mitigation. Their focus on automation and material efficiency promotes sustainability by reducing waste and increasing the structural strength of bridges [81]. Roy (2024), addressing smart cities, demonstrated green computing and IoT in creating sustainable cities. With technologies for reducing waste, generating renewable energy, and optimizing urban environments, his work helps make smart cities more sustainable. However, the barriers to their deployment in the real world scenarios, such as scalability and infrastructure readiness, were also identified [82]. Rath et al. (2024) dedicated to AI and IoT smart manufacturing within computer-integrated manufacturing (CIM) environments. They demonstrated how such technologies could drive efficiency, reduce environmental footprints, and yield better products. They pushed the importance of predictive maintenance, supply chain optimization, and live quality control to improve manufacturing performance, even as data security and workforce upskilling were questioned [83].

Pollák et al. (2024) aimed to simplify AM processes through AI-driven error detection in real time and smart monitoring systems, reducing defects and increasing production capacity. These studies revealed that AI in AM can reduce human involvement, enabling accurate and error-free manufacturing [84]. Similarly, Johnson and Jonah (2024) pointed to AM's ability to revolutionize product design through design freedom, prototyping speed, and material efficacy. They concluded that AM can not only help with faster product development but is also sustainable, reducing material loss and enhancing the production process [85]. Lastly, Zheng et al. (2024) studied the use of plasma cutting in the deconstruction of discarded railroad wagons and proposed it as an environmentally friendly substitute for flame cutting. Plasma cutting meant smaller heat-affected areas, reduced thermal deformation, and improved automation, making rail recycling more efficient and sustainable [86].

The above literature is summarized in Table 2, which includes columns detailing the author, topic, methodology, and outputs.

Table 2. Summary of Reviewed Literature with Details on Author, Topic, Methodology, and Outputs

Author	Topic	Methodology	Outputs
Mohd Yazid Md Taib, Zulkifli Mohamed Udin, Abdullah Hj Abdul Ghani	The impact of green management and technology in electrical and electronics manufacturing in business sustainability in Malaysia (2015)	Questionnaire survey with cross-sectional design; simple random sampling; pilot testing with 40 respondents; factor analysis, construct validity, and reliability testing.	Significant relationship between GM and GT and business sustainability; recommended holistic implementation; provided guidance for stakeholders on environmental and sustainability practices.
Liu Peng, Dillon K. Zhou, Yan Jianlin, Zhou Yuan, Xue Lan	Promoting Green Manufacturing Technology Diffusion Using Innovative Policy Implementation Methods (2016)	Case study on EMUP in Dongguan City; evaluation of public policies, subsidies, and energy performance contracts.	Identified barriers to technology diffusion; highlighted success factors like targeted subsidies; recommended enhancing financial mechanisms and stakeholder coordination.
Rakshith Badarinath, Vittaldas V. Prabhu	Advances in Internet of Things (IoT) in Manufacturing (2017)	Service-oriented architecture (SOA) four-layer model; review of IoT applications in manufacturing.	Proposed IoT framework; demonstrated energy-aware manufacturing, predictive maintenance, and shop floor automation; highlighted real-world use cases.
R. C. Yadav	Development of Universal Ultimate Total Green Chemistry and Eco-Agriculture for	Introduction of "smart nature agriculture"; integration of nitrogen/carbon cycles	572 quintals per hectare yield; reduced GHG emissions; outlined universally applicable agricultural techniques.

	Sustainable Productivity (2018)	and raised bed configurations.	
Sarafadeen Azeez, Esther T. Akinlabi	Sustainability of manufacturing technology: friction stir welding in focus (2018)	Analysis of welding parameters and energy use; use of bivariate Weibull approximation model.	Established link between heat input and weld joint reliability; recommended closed energy system for sustainability.
Aleksey Ignatov, Rustam Subkhankulov	Eco-friendly technology of manufacturing complex products made of composites (2019)	Experimental research on porosity control using hot directed air streams; optimization of PCM manufacturing methods.	Reduced energy costs; achieved 0.72% porosity in composites; improved worker safety and environmental impact in production.
Kenn Steger-Jensen, Hans-Henrik Hvolby, Iskra Dukovska-Popovska, Sven Vestergaard, Carsten Svensson	Enabling Green Manufacturing Using Advanced Planning and Scheduling (APS) Technology (2019)	Case study with Danish industries, data collection, and simulation models to optimize machine allocation, batch sizes, product mix, and energy consumption	Green manufacturing through APS integration, focusing on reducing waste, energy consumption, and emissions
W. Terouzi, A. Oussama	Development of Sustainable Multivariate Analytical Approach for Smart Factories (2019)	Combination of ATR-FTMIR and multivariate data analysis, applied to green bean fruit samples	Improved quality control for agro-food factories, enhancing efficiency and reliability
Kai Zhang, Wu Zhao, Xin Guo, Ling Chen	Smart Knowledge Application Methods for Green Manufacturing (2020)	Development of a smart knowledge application method using a design matrix and machine learning; case study on waste circuit board recycling	Sustainable manufacturing by linking design processes with necessary knowledge, supported by machine learning
Fernando E. García-Muiña, María Sonia Medina-Salgado, Anna Maria Ferrari, Marco Cucchi	Sustainability Transition in Industry 4.0 and Smart Manufacturing with the Triple-Layered Business Model Canvas (2020)	Triple-Layered Business Model Canvas, case study on ceramic tile manufacturer adopting Industry 4.0 for sustainability	New sustainable business model incorporating environmental, economic, and social sustainability
Tariq Samad, Rolf Bienert	Smart Manufacturing and Smart Grids (2020)	Discussion on smart grid technologies in manufacturing, with approaches like Direct Load Control, Automated Demand Response, and Microgrids	Enhanced energy efficiency through smart grids, contributing to green manufacturing
Abba Kyari Buba, Othman Ibrahim	Behavioural Model for Decision-Makers' Intention to Adopt Green IT in Nigerian Manufacturing Industries (2020)	Survey-based quantitative study with PLS-SEM for data analysis; pilot study on Nigerian manufacturers	Framework for adopting Green IT in Nigerian manufacturing industries, focusing on environmental sustainability and compliance with regulations
Michele Calì	Smart Manufacturing Technology (2021)	Focus on digitalization across sectors, autonomous processes, sustainability, and innovation	Promotes green manufacturing, enhances efficiency, innovation, and sustainability through smart technologies; proposes new methodologies for innovation and productivity.
Martin Plank, Sebastian Thiede, Christoph Herrmann	Versatile IT-system architecture for smart manufacturing solutions: the example for green manufacturing (2021)	IT-based solutions in manufacturing, focusing on green manufacturing and smart technologies	Proposes a versatile IT-system architecture to optimize resources, reduce waste, and enhance efficiency and sustainability in manufacturing.
Liisa Hakola, Elina Jansson, Romain Futsch, Tuomas Happonen, Victor	Sustainable roll-to-roll manufactured multi-layer smart label (2021)	Development of sustainable multi-layer smart labels through	Created a sustainable electronic device (anti-counterfeit label), demonstrating a high yield, good performance, and enhanced recyclability.

Thenot, Gael Depres, Aline Rougier, Maria Smolander		roll-to-roll printing using paper substrates	
Paula Fraga-Lamas, Sérgio I. Lopes, Tiago M. Fernández-Caramés	Green IoT and Edge AI as Key Technological Enablers for a Sustainable Digital Transition towards a Smart Circular Economy (2021)	Research on the integration of Green IoT (G-IoT) and Edge AI for sustainability	Highlights challenges and solutions for integrating G-IoT and Edge AI to reduce carbon footprints, focusing on smart circular economy and sustainable industrial applications.
Arturo Molina, Pedro Ponce, Jhonattan Miranda, Daniel Cortés	Sensing, Smart and Sustainable Manufacturing Processes (2021)	Study on emergent manufacturing technologies optimizing productivity, energy, water, and hazard emissions	Examines the role of new technologies in transforming materials into innovative products while optimizing resource use and minimizing emissions, promoting sustainable manufacturing.
Yuanyuan Li, Dechao Han	Construction of manufacturing green innovation system based on big data and artificial intelligence (2022)	Focus on using big data and AI for creating a green innovation system in manufacturing	Proposes a green innovation system framework with four modules to enhance eco-friendly design, production, and service, fostering sustainable economic development in manufacturing.
Edwin Gevorkyan, Jarosław Chmiel, Bogusz Wiśnicki, Tygran Dzhuguryan, Miroslaw Rucki, Volodymyr Nerubatskyi	Smart Sustainable Production Management for City Multifloor Manufacturing Clusters: An Energy-Efficient Approach to the Choice of Ceramic Filter Sintering Technology (2022)	Development of a model and indicators for energy efficiency, analysis of ceramic sintering processes, use of modern ceramic micro- and nanopowders	Reduction of sintering temperature by 20%, shortened thermal cycle by 19%, up to 40% electricity savings, energy-efficient production of ceramic filters
Min-Hwa Chi	IC Technologies and Systems for Green Future (2022)	Exploration of IC designs, integration of hardware/software in smart systems, focus on 3DIC, energy efficiency, and smart manufacturing	Development of low power consumption 3DIC, smart manufacturing techniques to reduce carbon emissions, application in clean energy, automotive, and smart cities
Yoon G. Kim, Richard P. Donovan, Yutian Ren, Shijie Bian, Tongzi Wu, Shweta Purawat, Anthony J. Manzo, Ilkay Altintas, Bingbing Li, Guann-Pyng Li	Smart Connected Worker Edge Platform for Smart Manufacturing: Part 1: Architecture and Platform Design (2022)	Development of an IoT-enabled edge platform for small and medium-sized manufacturers using low-cost sensors and cloud computing	Enhances data-driven decision-making, improved productivity, cost-effective adoption of smart manufacturing
Binbin Wu, Bangjun Gao, Xu Wei, Hongxun Wang, Yang Yi, Premalatha R	Sustainable Food Smart Manufacturing Technology (2022)	Framework development for evaluating sustainable food technologies, empirical evaluation methods	Identifies suitable technologies for SFIMT, promotes sustainability in food processing, supports customization, and resource-efficient practices
Bikash Koli Dey, Jeryang Park, Hyesung Seok	Carbon-emission and waste reduction of a manufacturing-remanufacturing system using green technology and automated inspection (2022)	Optimization of production plans, integration of green technology and automated inspection systems	2.81% reduction in carbon emissions, 2.37% reduction in waste, 18.26% cost reduction, improved environmental and economic sustainability
Jinying Han, Rui Hu, Qiaoya Zhang, Hongru Zhang	Research on Green Technology Innovation in Manufacturing Firms from ESG Perspective (2023)	Assessment of environmental impact, renewable energy adoption, circular economy principles,	Adoption of renewable energy, optimized resource use, reduced carbon emissions and waste, enhanced ESG performance through smart manufacturing and sustainable supply chains

		data-driven manufacturing	
Pandwe Aletha Gibson	Shortening the Supply Chain through Smart Manufacturing and Green Technology (2023)	Analysis of supply chain inefficiencies and IoT platform development	Proposed a PaaS manufacturing sharing service, an IoT platform for better coordination, eco-friendly inputs, and efficient distribution.
Wai Yie Leong, Yuan Zhi Leong, Wai San Leong	Smart Manufacturing Technology for ESG Sustainability (2023)	Emphasized smart manufacturing's role in ESG, data-driven optimization	Found that SMT reduces environmental impact, improves labor conditions, and enhances governance practices.
Agnieszka Deja, W. Ślączka, Lyudmyla Dzhuguryan, Tygran Dzhuguryan, Robert Ulewicz	Green Technologies in Smart City Multifloor Manufacturing Clusters: A Framework for AM Management (2023)	Development of a multi-floor facility layout model for additive manufacturing	Developed a new model for AM in urban environments, optimizing space and resource use, ensuring sustainability and circular economy alignment.
Yang Shen, Xiuwu Zhang	Intelligent Manufacturing, Green Technological Innovation, and Environmental Pollution (2023)	Surveys and data analysis of manufacturing firms	Showed intelligent manufacturing and green technologies reduce environmental pollution, improve efficiency, and enhance sustainability in manufacturing.
Lin Zhu, Xiaoming Li, Yao-Min Huang, Fangyuan Liu, Cheng Yang, Dongyang Li, Hongpeng Bai	Digital Technology and Green Development in Manufacturing: Evidence from China and 20 Other Asian Countries (2023)	Panel data analysis using a two-way fixed-effects model	Found a positive correlation between digital economy and Green Total Factor Productivity (GTFP), with human capital and trade competitiveness as key variables.
Ahmad Aminzadeh, Davood Rahmatabadi, Mostafa Pahlavani, Mahmoud Moradi, Jonathan Lawrence	Smart Laser Welding: A Strategic Roadmap Toward Sustainable Manufacturing in Industry 4.0 (2023)	Integration of Industry 4.0 technologies into laser welding processes	Demonstrated how IoT, big data, and sensor-based monitoring in laser welding can optimize processes, reduce defects, and promote sustainable manufacturing.
Sucheta Agarwal, Kuldeep K. Saxena, Vivek Agrawal, Jitendra Dixit, Chandra Prakash, Dharam Buddhi, K A Mohammed	Prioritizing the barriers of green smart manufacturing using AHP in implementing Industry 4.0: a case from Indian automotive industry (2024)	Analytical Hierarchy Process (AHP)	Identification and prioritization of nine significant barriers to GSM implementation: Financial Constraints, Supplier Issues, Data Security, Lack of Understanding, Inadequate Management Support, Data Interface Problems, Lack of Government Support, Employee Training Issues, Resistance to Change, Technological Constraints.
Wei Zhang, Shuai Ye, Sachin Kumar Mangla, Ali Emrouznejad, Malin Song	Smart Platforming in Automotive Manufacturing for NetZero: Intelligentization, Green Technology, and Innovation Dynamics (2024)	Mixed Regression Method	Positive impact of smart product platforms on green technology innovation, mediated by innovation input; Moderating effect of intelligentization on the relationship; Variability in impact based on regional and ownership attributes.
Jinke Li, Luyue Ji, Shuang Zhang, Yanpeng Zhu	Digital technology, green innovation, and the carbon performance of manufacturing enterprises (2024)	Resource orchestration theory and signaling theory	Significant improvement in carbon performance through digital technology; Green innovation as a mediator; Environmental information disclosure enhances carbon performance; Impact varies by industry and enterprise strategy.
Tiancheng Liu, Chao Zhu, Zengyi Tong, Dongchao Luo	Research on smart manufacturing technology of reinforcing bars for bridge precast concrete structure (2024)	Building Information Modeling (BIM) and integer programming algorithm	Enhanced efficiency and quality in processing reinforcing bars using BIM technology and intelligent tooling; Reduced material waste and improved disaster resilience of bridges.
Siddhartha Roy	A Study of the Future Generation of Smart	Qualitative analysis	Integration of green computing, IoT, and smart technologies for sustainable and efficient smart cities; Focus on renewable energy, waste

	Cities Using Green Technology (2024)		management, and urban development challenges.
Kali Charan Rath, Alex Khang, Srimant Kumar Mishra, Prabin Kumar Patnaik, Gopal Kurushna Mohanty, Taraprasanna Dash	Integration of Artificial Intelligence and Internet of Things Technology Solutions in Smart Manufacturing (2024)	Case studies, Literature review	AI and IoT integration improves manufacturing efficiency, sustainability, and product quality; Applications in production planning, inventory management, predictive maintenance, quality control, and supply chain optimization; Challenges in data security, interoperability, workforce training, and infrastructure.
Martin Pollák, Peter Gabštur, Marek Kočiško	Prediction of Errors in the Field of Additive Manufacturing Technology (2024)	Developed a camera system for real-time monitoring of 3D printing using the OctoPrint Nexus AI plug-in. Designed a monitoring device for Creality Ender 3 printers.	Improved error detection and reduction in defects during 3D printing, enhanced quality of printed parts, and facilitated automated monitoring for industrial applications.
Pradeep Johnson, Jonah	Additive Manufacturing: Revolutionizing Modern Manufacturing Technology (2024)	Analyzed the benefits of additive manufacturing, including rapid prototyping, material versatility, and supply chain efficiency.	Identified sustainability benefits, improved product development cycles, and highlighted the transformative potential of additive manufacturing for industrial growth and reduced environmental impact.
Wangwang Zheng, Shan Huang, Shanwen Wu, Chao Shi	Research on Plasma Disassembly Technology of Scrapped Railway Wagons for Green Manufacturing (2024)	Introduced plasma cutting technology with automated robotics for railway wagon disassembly. Compared with traditional flame cutting methods.	Achieved improved disassembly efficiency, reduced thermal deformation, and promoted green manufacturing through sustainable recycling practices and reduced waste in the railway industry.

8. Conclusion

In this in-depth overview on green manufacturing in the era of smart technologies, there are a number of takeaways and considerations for industries that want to become sustainable. It is a must to incorporate smart technologies like IoT, AI, and digital twins for better usage of resources and less waste in manufacturing. Such technologies allow us to monitor and gather data all the time for decision-making and productivity. We have seen from companies like Honda, Hitachi, and S.C. Johnson that if a company can incorporate sustainable technologies, it can greatly diminish carbon emissions and waste. S.C. Johnson's zero waste and responsible sourcing policy, for example, demonstrates sustainability commitment. Digital technology can be key to moving conventional manufacturing to more sustainable models. Companies can be empowered to operate more efficiently through the data analytics and machine learning resulting in better energy efficiency and fewer ecological footprints. The findings of this review reflect the United Nations SDGs on the theme of ethical consumption and production. Environmental, social, and economic benefits come from sustainable manufacturing. The comments herein are of interest to practitioners, policymakers, and researchers. Knowledge of how technology and industry work together is key to sustainable manufacturing initiatives. The paper concludes that smart technology and sustainable manufacturing should be aligned in order to achieve both industry and sustainability objectives at the global level. Technological and sustainability cooperation is the key to more sustainable and responsible manufacturing.

Author Contribution Statement

The author, Parankush Koul, was solely responsible for the conception, design, literature review, analysis, and writing of this review article. The author has read and approved the final manuscript.

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