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Digital Green Innovation towards Industry 5.0 and Society 5.0: A Mini-Review

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Abstract

This paper comprehensively delves into digital green innovation within the manufacturing industry against the backdrop of the progression towards Industry 5.0 and Society 5.0 as well as global economic trends. The manufacturing sector, a crucial pillar for economic growth, now contends with significant hurdles in its quest for sustainability. Digital green innovation, skillfully merging digital technologies and green principles, has thus emerged as a key driver to steer the industry towards the aspired future. It meticulously analyzes how advanced digital technologies function; the IoT enables real-time, detailed production line monitoring like in automobile manufacturing to ensure smooth operations, big data analytics guides smart decision-making, artificial intelligence transforms quality control and scheduling, and blockchain bolsters product traceability trust. Green innovation, covering green manufacturing, circular economy, and low-carbon technologies, builds the foundation of a sustainable ecosystem, spurred by government policies, market demands, technological advances, and corporate strategies. Its practical applications are extensive, with intelligent manufacturing creating intelligent factories and robust green supply chains, product life cycle management optimizing from start to finish, energy management reducing consumption and leveraging renewables, and waste management initiating a circular economy. The benefits are three-pronged: environmentally cutting emissions and conserving resources, economically slashing costs, enhancing productivity and competitiveness, and socially generating jobs and enhancing corporate reputations. Future research will focus on interdisciplinary integration, integrating emerging technologies into supply chains, and micro-macro coordination to fuel continuous innovation in the manufacturing industry in the new era.

Subject Areas

Artificial Intelligence, Linguistics

Keywords

Digital Green Innovation, Industry 5.0, Society 5.0, Circular Economy, Artificial Intelligence

1. Introduction

In the current global economic upsurge, the manufacturing industry undeniably assumes a pivotal role. As the core of the real economy, it serves not only as a key driver of GDP growth across countries but also as a crucial engine for absorbing a vast labor force and fostering the coordinated development of upstream and downstream industries [1]. Ranging from automotive manufacturing to electronics assembly, and from precision machinery to the production of daily consumer goods, the manufacturing industry pervades every corner of our lives, deeply ingrained in all aspects and contributing significantly to the prosperity of the global economy [2].

Nevertheless, as we progress towards Industry 5.0 and Society 5.0, the manufacturing sector is confronted with unprecedented challenges in sustainable development [3]. On one hand, the traditional manufacturing model, which is highly dependent on resource consumption, now faces exacerbated issues like the energy crisis and raw material shortages [4]. These problems are leading to a continuous escalation of costs and severely restricting the development prospects, impeding the industry's smooth transition towards the more advanced Industry 5.0 stage. On the other hand, the environmental pollution resulting from extensive production, characterized by the emission of waste gas, wastewater, and solid waste, has spurred a multitude of ecological problems [5]. This has not only caused harm to the environment but also led to an increasing public outcry, as society, in the context of aspiring for Society 5.0, places higher expectations on environmental protection and sustainable development [6].

In response to these challenges, digital green innovation has emerged as a game-changer [7]. "Digital green innovation" refers to an innovative paradigm that, under the backdrop of Industry 5.0 and Society 5.0, integrates advanced digital technologies such as IoT, big data, AI, and blockchain with green concepts including green manufacturing, circular economy, and low-carbon technologies [8]. This approach drives comprehensive reforms in manufacturing processes, management models, and product design to achieve efficient resource utilization while minimizing environmental impact [9]. Digital green innovation epitomizes a profound integration of digital technologies and the concept of green innovation, precisely aligning with the development trends of Industry 5.0 and Society 5.0. By harnessing state-of-the-art digital tools such as big data, artificial intelligence, and the

Internet of Things (IoT), it conducts a comprehensive overhaul of the manufacturing industry's production processes, management models, and product design [10] The overarching goal is to achieve highly efficient resource utilization and minimize environmental impacts, thereby laying a solid foundation for the industry's progression towards Industry 5.0. For example, with the IoT, real-time monitoring of equipment energy consumption becomes possible, allowing for immediate adjustments to optimize energy use [11]. Artificial intelligence can be employed to meticulously optimize production schedules, significantly reducing the scrap rate and enhancing overall production efficiency [12]. Digital design techniques enable the minimization of material waste, ensuring that resources are used more judiciously [13].

Delving deeply into the significance of digital green innovation for the sustainable development of the manufacturing industry is of paramount importance [14]. This not only provides a viable pathway for the manufacturing industry to break free from its current constraints, undergo transformation and upgrading, and achieve long-term, stable development in the journey towards Industry 5.0 but also equips it to contribute substantially to global efforts in tackling major challenges such as climate change and resource conservation [15]. In doing so, it propels human society forward in the pursuit of a green and prosperous future envisioned by Society 5.0 [16].

The research team implemented a systematic literature search strategy to ensure comprehensive coverage and representativeness. The search primarily utilized authoritative academic databases such as Web of Science, Scopus, CNKI, and IEEE Xplore. Core search keywords included "digital green innovation", "Industry 5.0", and "Society 5.0", supplemented by related terms like "circular economy", "artificial intelligence" and "green manufacturing". The time frame was limited to 2018-2024, a critical period when Industry 5.0 concepts were being deeply implemented alongside Society 5.0 principles, and digital green innovation accelerated, effectively reflecting the latest advancements and research trends in the field. Priority was given to studies involving both digital technology applications and green innovation practices closely tied to manufacturing scenarios. Ultimately, 112 valid papers were selected as the core basis for review analysis, providing solid academic support for theoretical discussions and practical evaluations in this study.

2. Theoretical Foundations

In the evolution of industrial development, "Industry 4.0" takes digitalization and intelligence as its core. Through technologies such as the Internet of Things, big data, and artificial intelligence, it realizes the interconnection and autonomous decision-making of production equipment, materials, and systems. The focus is on enhancing production efficiency, reducing costs, and achieving flexible manufacturing. "Industry 5.0" further extends on this basis, focusing on sustainability and people-oriented principles. While retaining the advantages of digitalization and intelligence, it places greater emphasis on the coordination between production and the environment as well as the integration of technology and human needs, aiming to build a sustainable industrial ecosystem with greater social value. This evolution has established sustainable development as a core indicator, directly promoting the deep integration of digital technology and green concepts and serving environmental protection goals, providing a unique perspective for digital green innovation.

In the context of Industry 5.0 and Society 5.0, digital technologies are the driving force behind the transformation of the manufacturing industry [17]. The Internet of Things (IoT), functioning as a perceptive sensing network, deploys sensors across workshops [18]. These sensors gather data on equipment and processes, enabling enterprises to anticipate malfunctions in advance and conduct precise maintenance [19]. Automotive manufacturing companies, for example, rely on this to keep their production lines running smoothly, which is crucial for meeting the high-quality and efficient production requirements of Industry 5.0 [20]. Big data is proficient in analyzing the vast amount of information collected by the IoT. By uncovering patterns, it provides decision-making support. It optimizes procurement and production plans according to order, market, and supply data, thus avoiding inventory risks and reducing costs, and aligning with the economic and resource-efficient aspects of Industry 5.0 [21]. Artificial Intelligence (AI), with its powerful learning capabilities, deeply infiltrates into the manufacturing process [22]. It can accurately detect defects during quality inspection and dynamically plan the optimal sequence during scheduling, significantly enhancing efficiency [23]. This not only improves the competitiveness of enterprises but also contributes to the intelligent manufacturing concept of Industry 5.0 [24]. Blockchain, with its tamper-proof feature, ensures product information transparency [25]. In high-end electronics manufacturing, it records the entire trajectory of components, enhancing market trust, which is essential for building a reliable and transparent supply chain in Society 5.0 [26].

Green innovation serves as the bedrock for the sustainable development of the manufacturing industry [27]. Green manufacturing instills environmental thinking from the very start of the design phase [28]. In the furniture industry, for instance, the selection of biodegradable materials and the improvement of manufacturing processes help reduce material waste and waste emissions, contributing to the sustainable consumption and production goals in Society 5.0 [29]. The circular economy promotes the closed-loop circulation of resources [30]. Electronic waste, after being disassembled and refined, can return precious metals to the production line, extending the lifespan of resources [31]. This resource-recycling approach is a key aspect of sustainable development in both Industry 5.0 and Society 5.0. Low-carbon technologies focus on carbon reduction [32]. Steel enterprises, for example, skillfully use waste heat to generate electricity and upgrade energy-saving equipment, reducing carbon emissions and alleviating environmental pressure [33]. This is in line with the low-carbon and environmentally friendly requirements of Industry 5.0 and Society 5.0 [34].

The theoretical framework of digital green innovation organically integrates the advantages of both digital technologies and green innovation [35]. Taking product life-cycle management as an example, it uses digital means to establish an information hub covering all stages from design to recycling [36]. Through in-depth analysis and optimization by big data and AI throughout the process, and by integrating green concepts to implement practices such as environmentally friendly material selection, energy conservation and consumption reduction, and recycling and regeneration, it jointly propels the manufacturing industry towards a new path of green and intelligent high-quality development [37]. This new path is in line with the overarching goals of Industry 5.0, which emphasizes the integration of human-centered intelligence and sustainable development, and Society 5.0, which aims for a human-friendly and sustainable society.

3. Drivers of Digital Green Innovation

3.1. Policy-Driven: Guiding the Direction of Digital Green Innovation

In the journey of the manufacturing industry towards digital green innovation, government policies, regulations, and standards act like bright beacons, playing an indispensable leading and promoting role [38]. On the one hand, policy support injects strong impetus into enterprises [39]. Many countries and regions have introduced special subsidy policies to encourage manufacturing enterprises to introduce digital and green technologies to transform their production lines [40]. For example, the European Union has established the "Green Digital Transformation Fund" to provide financial support for eligible small and medium-sized enterprises [41]. The funds can be used to purchase IoT monitoring equipment, energy-efficient CNC machining centers, etc., reducing the transformation costs of enterprises and accelerating technological upgrading [42]. This is in line with the strategic direction of promoting sustainable development in Industry 5.0 and Society 5.0, where governments play a crucial role in guiding industries to adopt advanced and environmentally friendly technologies.

On the other hand, strict regulations and standards form a solid constraint. The increasingly stringent environmental protection regulations compel enterprises to control pollution emissions and improve resource utilization efficiency [43]. For instance, China's "Measures for Cleaner Production Auditing in the Manufacturing Industry" requires enterprises to regularly evaluate their production processes and identify potential for energy conservation and emission reduction [44]. Enterprises that fail to meet the standards face the risk of production restriction and rectification. Meanwhile, green product certification standards prompt enterprises to incorporate environmental considerations into the design stage [45]. Only products that meet the relevant standards can obtain market access, forcing enterprises to actively carry out digital green innovation and develop more environmentally friendly products. This is essential for building a sustainable consumption and production pattern in Society 5.0.

3.2. Market-Driven: Stimulating the Vitality of Digital Green Innovation

The market, as a barometer of economic activities, contains various factors that continuously stimulate the vitality of digital green innovation [46]. The transformation of consumer demand is one of the key drivers. With the improvement of living standards, consumers' attention to the environmental protection attributes and quality traceability of products has soared [47]. They prefer to buy products labeled with "green energy-saving" and whose production processes can be traced throughout [48]. This prompts enterprises to use blockchain and big data technologies to make product information transparent and adopt green innovation processes to improve the environmental protection quality of products to meet market demands. In the context of Industry 5.0 and Society 5.0, where consumers are more conscious about sustainable development, meeting these demands is crucial for enterprises to succeed [49].

Intense market competition also plays an important role. In the current environment flooded with homogeneous products, digital green innovation has become a sharp weapon for enterprises to stand out [50]. Manufacturing enterprises that take the lead in using artificial intelligence to optimize production processes and reduce energy consumption can provide higher quality products at a lower cost, seize market share, and force their peers to follow suit, forming a virtuous cycle of innovation competition [51]. In addition, the need to shape a good brand image cannot be ignored. Enterprises convey the concept of sustainable development to society through practicing digital green innovation [52]. For example, Apple uses recyclable materials in product packaging and publishes the product carbon footprint, enhancing brand reputation and attracting more consumers with strong environmental awareness, further consolidating its market position [53]. This is in line with the brand building and social responsibility requirements in Society 5.0.

3.3. Technology-Driven: Consolidating the Foundation of Digital Green Innovation

Technological progress and innovation are undoubtedly the foundation for the vigorous development of digital green innovation [54]. The rapid development of new-generation information technologies has provided infinite possibilities for the transformation of the manufacturing industry [55]. The leap in big data storage and analysis capabilities enables enterprises to process vast amounts of production data and accurately locate high-energy-consuming and low-efficiency links, providing a basis for optimized decision-making [56]. For example, Schneider Electric analyzed the energy consumption data of its global factories through big data and discovered energy waste problems in specific periods. By making targeted adjustments to the production plan, it achieved an energy saving of 15%. This kind of data-driven optimization is a key aspect of intelligent manufacturing in Industry 5.0 [57].

The continuous breakthroughs in artificial intelligence have expanded the application boundaries [58]. Deep learning algorithms help robots perform precise operations in complex production environments, reducing the scrap rate; intelligent scheduling systems optimize logistics distribution in real time, reducing transportation carbon emissions [59]. The maturity of IoT technology has made everything interconnected a reality. Factory equipment can communicate with each other and work in real-time collaboration, improving overall operational efficiency [60]. At the same time, innovation achievements in fields such as new energy technologies and materials science have also contributed to green manufacturing. High-performance lithium batteries have replaced traditional lead-acid batteries, greatly reducing the environmental risks of energy storage equipment; new biodegradable biomaterials have been applied in the packaging field, reducing plastic pollution [61]. Together with digital technologies, they have laid a solid foundation for digital green innovation in the manufacturing industry.

3.4. Enterprise Internal-Driven: Gathering the Forces of Digital Green Innovation

Internal elements of enterprises play a crucial role in gathering the forces of digital green innovation [62]. The orientation of enterprise strategy is of vital importance. Enterprises that clearly incorporate digital green innovation into their long-term development plans will allocate resources preferentially [63]. For example, the BMW Group has formulated a "Digital + Sustainable" dual-core strategy and invests billions of dollars annually in research and development of electric vehicles and smart factory technologies, promoting innovation implementation from the top management [64]. This is in line with the strategic transformation requirements of enterprises in Industry 5.0, which focus on both digitalization and sustainability.

The organizational culture atmosphere affects employees' enthusiasm for innovation. An enterprise culture that advocates openness, collaboration, and the courage to try encourages employees to communicate across departments and share ideas and experiences of digital green innovation, which can accelerate the innovation process [65]. Google has implemented the "20% free time" system, allowing employees to use part of their working time to explore innovative projects of interest. This has generated many digital green-related ideas, and some have been transformed into practical technologies applied in production [66].

The innovation ability of enterprises themselves is the internal support for digital green innovation [67]. Enterprises with strong R&D teams and perfect innovation management processes can transform new technologies and concepts into actual productivity more quickly [68]. Huawei, with its profound technical accumulation and efficient R&D system, has achieved fruitful results in areas such as 5G communication-assisted smart factory construction and green energy-saving base station research and development, demonstrating the powerful effectiveness of enterprise internal drivers in digital green innovation [69].

3.5. Synergy-Driven: Forging the Joint Force of Digital Green Innovation

Digital green innovation is not the result of a single factor acting in isolation but the joint force forged by the synergy of multiple aspects such as policy, market, technology, and enterprise internal factors [70] Policy guidance creates a macro environment for innovation, market demand provides directional guidance, technological progress provides means of support, and enterprise internal implementation provides micro power [71]. When the government introduces policies to encourage the development of new energy vehicles, the market consumers have a high demand for environmentally friendly travel, and battery technology, autonomous driving technology, etc. develop rapidly. Automobile enterprises adjust their strategies and invest in research and development accordingly [72]. All parties work together to promote the vigorous development of the new energy vehicle industry, which has become a model case of digital green innovation [73]. Only by fully recognizing and giving play to the synergistic effects of various driving factors can the manufacturing industry make great strides on the path of digital green innovation and achieve the grand goal of sustainable development in line with the development trends of Industry 5.0 and Society 5.0 [74].

4. Practical Applications of Digital Green Innovation

4.1. Intelligent Manufacturing: Reshaping the New Paradigm of Green Manufacturing

In the wave of digital green innovation, intelligent manufacturing has become a key force in the transformation and upgrading of the manufacturing industry, reshaping a new paradigm of green manufacturing [75]. As the core carrier of intelligent manufacturing, smart factories deeply integrate digital technologies and green concepts. Inside the factory, IoT sensors, like precise nerve endings, are widely distributed in various production equipment, production lines, and warehousing and logistics links, collecting data comprehensively and in real-time, covering key information such as equipment operating status, energy consumption, and material flow [76]. This massive amount of data is quickly transmitted to the background control system through high-speed networks and processed by big data analysis and artificial intelligence algorithms to transform into precise decision-making instructions.

For example, Siemens' Amberg Electronics Factory in Germany relies on digital twin technology to create a virtual factory model that accurately maps with real production [77]. Engineers can operate the virtual model to simulate and optimize the production process and equipment layout in advance. Not only has the product production cycle been shortened by 30%, but also, with the help of the intelligent energy management system, the start-stop and power output of equipment can be regulated in real-time, achieving a 20% reduction in energy consumption per unit of output value. This kind of intelligent operation is in line with the requirements of high-efficiency and low-carbon production in Industry 5.0.

Green supply chain management is an extension of intelligent manufacturing at the industrial chain level [78]. By leveraging the immutable and traceable characteristics of blockchain technology, it ensures that suppliers follow green environmental protection standards from the source of raw material procurement, such as ensuring that the mining process complies with ecological norms and that materials are recyclable [79]. In the logistics and distribution stage, big data is used to optimize transportation route planning, reducing transportation mileage and carbon emissions [80]. The intelligent warehousing management system is used to precisely control inventory levels, reducing warehousing space occupation and energy consumption, realizing green control throughout the process from raw material procurement to finished product delivery. This is crucial for building a sustainable supply chain in the context of Society 5.0.

4.2. Product Life Cycle Management: The Digital Green Link Throughout the Whole Process

Product life cycle management (PLM), with the help of digital technologies, weaves a tight digital green link for the entire process of a product from conception to disposal [81]. In the product design stage, technologies such as computer-aided design (CAD) and virtual reality (VR) shine. Designers use CAD software for three-dimensional modeling to accurately simulate product structures and performances and quickly optimize the design through parametric design, reducing the number of physical prototype productions and material waste. At the same time, green design concepts are incorporated, environmentally friendly materials are selected, and energy consumption is estimated based on product usage scenarios to ensure that the product is anchored in a green direction from the initial design. This is in line with the sustainable design principles in Industry 5.0 and Society 5.0.

In the production stage, the digital manufacturing execution system (MES) coordinates overall [82]. Based on real-time data such as order requirements, equipment capacity, and material inventory, it conducts intelligent production scheduling, optimizes the production sequence, and reduces energy losses caused by equipment idleness and frequent start-ups [83]. Through in-depth integration with automated production equipment, precise processing is achieved, the scrap rate is reduced, and material utilization is improved [84]. For example, Foxconn introduced MES in its mobile phone production line, increasing production efficiency by 25%, reducing the defective rate by 18%, and significantly reducing resource consumption.

During the product use stage, the IoT and big data help achieve intelligent operation and maintenance [85]. In the field of smart home appliances, sensors built into the equipment collect real-time operating data and upload it to the cloud. Enterprises provide users with personalized energy-saving suggestions based on data analysis, remotely diagnose faults, and issue early warnings for maintenance, extending the service life of the product, reducing the replacement frequency, and reducing resource consumption.

In the recycling stage, a digital traceability system is used to accurately identify the components and material compositions of products, providing clear guidance for disassembly, classification, and reuse [86]. For example, automotive manufacturing enterprises use QR codes, RFID and other identification technologies to record the materials and assembly processes of vehicle components, facilitating efficient recycling after scrapping and realizing a closed-loop resource cycle. This is an important part of the circular economy in Industry 5.0 and Society 5.0.

4.3. Energy Management: Illuminating the Path of Green Energy Efficiency

Energy management is an important practical field of digital green innovation. Digital technologies, like shining lights, illuminate the path for the manufacturing industry to improve green energy efficiency. In terms of energy efficiency improvement, enterprises rely on advanced energy management systems (EMS) to integrate scattered energy data collection points in the factory, covering multiple energy forms such as electricity, gas, and steam [87]. Through real-time monitoring and big data analysis, they accurately understand energy consumption patterns and identify high-energy-consuming links and time periods.

For example, Dow Chemical deployed EMS in its global factories and used machine learning algorithms to analyze vast amounts of energy data [88]. It was discovered that the capacity utilization rate of some production processes was low during the off-peak electricity price period at night [89]. Through optimized scheduling, the high-energy-consuming processes were moved to this period, and combined with equipment energy-saving renovations, the overall energy consumption was reduced by 12%. This kind of data-driven energy management is a key practice in Industry 5.0.

The utilization of renewable energy has also been deeply expanded due to digital technologies [90]. Smart microgrid technology has emerged. It integrates solar and wind power generation devices and is coordinated and controlled in real-time by the energy management system (EMS). Based on weather and electricity load forecast data, the energy supply mode is intelligently switched. Renewable energy is preferentially used, and surplus electricity is fed back to the grid. When there is sufficient sunlight and stable wind, the factory is preferentially powered by clean energy [91]. When it is insufficient, it seamlessly switches to the mains power to ensure a stable and reliable energy supply, helping enterprises gradually increase the proportion of renewable energy and move towards low-carbon development [92]. This is in line with the global goal of carbon neutrality in Society 5.0.

4.4. Waste Management: Opening a New Chapter of the Circular Economy

In the field of waste management, digital technologies have opened a new chapter of the circular economy [93]. In the waste reduction stage, the digital monitoring system of the production process plays a key role. By real-time monitoring of data on material input, product output, and waste generation, potential material savings are explored through data analysis [94]. For example, steel enterprises adopt this system to precisely control the ratio of steelmaking raw materials and optimize the smelting process, reducing slag generation by 15%. This kind of waste reduction measure is crucial for sustainable production in Industry 5.0.

In the recycling stage, the IoT and blockchain technologies help build an efficient recycling network [95]. In the recycling of waste electronic products, each recycled item is attached with an IoT tag to record information such as its source, type, and damage degree, facilitating rapid classification and sorting. Blockchain ensures the transparency and credibility of the recycling process, providing a basis for quality traceability in the subsequent reuse stage [96].

In the reuse stage, with the help of digital design and additive manufacturing technologies, recycled materials are transformed into high-value-added products [97]. For example, waste plastics are made into personalized industrial components and cultural and creative products through 3D printing, realizing a "gorgeous transformation" of waste, reducing the demand for virgin materials and expanding economic income channels [98]. This promotes the manufacturing industry to practice digital green innovation in the waste management dimension and move towards a sustainable future. This is an important manifestation of the circular economy in Industry 5.0 and Society 5.0.

4.5. Synergy and Integration: Playing the Movement of Digital Green Innovation

The various practical applications of digital green innovation do not exist in isolation but are synergistically integrated, jointly playing an exciting movement for the manufacturing industry to move towards sustainable development. Intelligent manufacturing provides an efficient operation platform and technical support for product life cycle management, energy management, and waste management. Product life cycle management, with its digital and green control throughout each link, defines the direction and optimizes the details for intelligent manufacturing. Energy management ensures the green power supply for production operations, while waste management realizes a resource closed loop, creating conditions for efficient energy utilization.

When an automotive manufacturing enterprise builds a smart factory, it applies the concept of product life cycle management to optimize the design, production, and recycling processes [99]. It uses the energy management system to reduce energy consumption and utilizes renewable energy. Through waste management, it realizes the recycling and remanufacturing of components [100]. Each link is closely coordinated, releasing the huge energy of digital green innovation, pushing the entire industry to stride towards a future of resource conservation, environmental friendliness, high efficiency, and intelligence, and contributing powerful strength to global sustainable development in line with the development trends of Industry 5.0 and Society 5.0.

However, digital green innovation has not been smooth sailing in practical application, and the high upfront investment has become one of the most significant constraints. For small and medium-sized enterprises with limited financial strength, deploying digital technologies such as Internet of Things sensors and artificial intelligence management systems, as well as green infrastructure, requires huge investment, which seriously hinders the advancement of their innovation process. In response to this, existing enterprises and relevant entities have explored multi-dimensional coping paths: First, set up special funds at the policy level. The EU's "Green Digital Transformation Fund" provides direct financing support for eligible small and medium-sized enterprises to purchase Internet of Things monitoring equipment through subsidies, significantly reducing the cost of transformation. Second, implement the strategy in stages. For instance, BMW Group first empresses digital green technologies in key links and then promotes them step by step based on benefit assessment to smooth the investment curve and balance input and return. Apart from financial constraints, data security risks should not be ignored either. Once the massive amount of data accumulated by the interconnected digital system during the production process is leaked, it will cause incalculable losses. In response to this, enterprises should establish a real-time network security system. For instance, Siemens has deployed an AI-driven anomaly detection system in its industrial Internet of Things network to immediately identify and handle potential threats, thereby minimizing risks to the greatest extent.

5. Impacts and Benefits of Digital Green Innovation

5.1. Environmental Benefits: Adding Green and Empowering the Earth

Digital green innovation is like a timely rain, bringing remarkable achievements in alleviating the global environmental crisis. Its environmental benefits are mainly reflected in three key dimensions: reducing carbon emissions, conserving resources, and minimizing waste.

In terms of reducing carbon emissions, the intelligent energy management system in intelligent manufacturing can regulate the energy consumption of factory equipment in real-time, precisely matching production requirements and avoiding energy waste. For example, Tesla's Gigafactory optimizes production processes and energy utilization through digital technologies, significantly reducing carbon emissions per unit of product [101]. Compared with traditional automotive manufacturing plants, the carbon dioxide emissions during the production of each vehicle are reduced by about 30%. Meanwhile, in the logistics link, transportation route planning driven by big data shortens delivery mileage, further cutting carbon emissions in the transportation process [102]. This aligns with the global efforts to combat climate change and move towards carbon neutrality in the context of Society 5.0.

Resource conservation has achieved remarkable results. Digital design tools in product life cycle management help enterprises make precise selections at the design stage, choosing environmentally friendly and efficient materials to reduce resource consumption from the source [103]. Taking the construction industry as an example, with the help of Building Information Modeling (BIM) technology, designers can accurately calculate the amount of building materials needed, avoiding over-purchasing and construction waste, and realizing a 10% - 15% reduction in the consumption of steel, cement, and other resources [42]. This is crucial for sustainable resource management in Industry 5.0.

Waste reduction is one of the highlights of digital green innovation. In the waste management link, the combination of digital monitoring systems and intelligent process optimization effectively reduces waste generation [104]. For example, an electronics manufacturing enterprise adjusts the parameters of the chip cutting process based on real-time monitoring data, reducing edge waste by 20%. Moreover, through the recycling network built with the IoT and blockchain, the recovery rate of waste electronic products is increased, reducing the pollution load of waste on the environment and laying a solid foundation for the sustainable development of the earth's ecosystem [105]. This is an important part of the circular economy in Industry 5.0 and Society 5.0.

5.2. Economic Benefits: Activating New Momentum for Industrial Development

Digital green innovation has injected strong vitality into the manufacturing industry at the economic level, mainly manifested as cost savings, efficiency improvements, and enhanced market competitiveness.

Cost savings run through the entire production process. The energy management system accurately identifies energy-saving opportunities, reducing electricity expenses [106]. Digital procurement platforms optimize the supply chain, lowering raw material procurement costs. For example, Unilever adopted an intelligent procurement system [107]. By analyzing factors such as the cost-effectiveness and delivery cycle of suppliers based on big data, it conducts precise procurement, reducing annual procurement costs by 8%. This kind of data-driven cost control is in line with the efficient operation requirements of Industry 5.0.

The efficiency improvement is immediate [108]. The intelligent factory and digital manufacturing execution system in intelligent manufacturing work together to shorten the production cycle and increase equipment utilization. After Foxconn introduced automated production lines and the MES system, the average production capacity of the production line increased by 30%, and the product delivery cycle was shortened from the original 15 days to 10 days, enabling it to quickly respond to market demands and seize the initiative. This is crucial for enhancing the competitiveness of enterprises in Industry 5.0.

Market competitiveness has been significantly enhanced due to digital green innovation. Consumers have a strong preference for environmentally friendly products. Enterprises win market share with green innovative products [71]. For example, Apple has continuously promoted digital green innovation. Its products, with low energy consumption and recyclable designs, attract global consumers. The brand's premium ability has increased, and its market share has steadily grown, standing out in the high-end electronics market. This is in line with the brand building and market expansion requirements in Industry 5.0 and Society 5.0 [109].

5.3. Social Benefits: Lighting up the Hope for Social Development

The social benefits of digital green innovation are equally remarkable, bringing many blessings to social development, covering employment opportunities, social responsibilities, and corporate image enhancement.

In terms of employment opportunities, although intelligent manufacturing initially reduces some repetitive labor positions, with the emergence of emerging positions such as digital green technology research and development and operation and maintenance, the overall employment structure has been optimized. For example, during the implementation of Germany's Industry 4.0 strategy, a large number of positions such as industrial IoT engineers and big data analysts were created, providing broad career development space for local young people. This is in line with the talent development and employment transformation requirements in the context of Industry 5.0.

Enterprises that practice digital green innovation actively assume social responsibilities, contribute to addressing climate change and resource protection, and win social acclaim [110]. For example, BYD has vigorously developed new energy vehicles and energy storage technologies, contributing to global carbon reduction and becoming a model of social responsibility. This is in line with the pursuit of social value in Society 5.0.

Corporate images have been significantly improved. The public has a high recognition of enterprises that are actively innovative and develop in a green way. Starbucks launched a green store plan, decorating stores with renewable energy and environmentally friendly materials. As a result, the store's customer flow increased by 10%, and the brand image was deeply rooted in people's hearts, achieving a win-win situation in economic and social benefits and injecting warm and strong positive energy into social development. This is in line with the corporate social responsibility and brand influence expansion requirements in Society 5.0.

6. Future Research Directions

With the in-depth practice of digital green innovation in the manufacturing industry, a series of cutting-edge and highly promising research directions have gradually emerged, paving the way for continuously propelling the industry towards a higher level of sustainable development.

6.1. In-depth Interdisciplinary Integration and Innovation Breakthroughs

Breaking traditional disciplinary barriers and promoting deeper interdisciplinary integration is a crucial step. On the one hand, the coordinated efforts of quantum computing, artificial intelligence, and advanced manufacturing processes warrant in-depth exploration. For example, in the precision manufacturing of aerospace components, the ultra-high-speed data processing capability of quantum computing combined with the intelligent optimization algorithms of artificial intelligence can perform real-time and precise regulation of complex manufacturing process parameters. This not only can improve the machining precision to the nanometer level but also significantly reduce the energy consumption and material waste caused by process debugging, breaking through the existing bottlenecks in manufacturing precision and efficiency. This kind of high-precision and efficient manufacturing is in line with the development requirements of Industry 5.0, which emphasizes advanced manufacturing technologies.

On the other hand, integrating bioscience and nanotechnology into the innovation and research and development process of green materials. By mimicking the self-assembly mechanism of biomolecules at the micro level and using nanotechnology to precisely manipulate the atomic and molecular structures of materials, multi-functional green materials with super performance can be developed. For instance, nanocomposite materials with high strength, high toughness, self-cleaning, and degradable characteristics can be developed and used in automobile and ship manufacturing. These materials can not only significantly reduce the weight of equipment and energy consumption but also decompose naturally at the end of the product's life cycle, reducing the environmental burden. This is in line with the sustainable material development needs in Industry 5.0 and Society 5.0, which focus on environmental protection and resource conservation.

6.2. All-Round Empowerment of Supply Chain Transformation by Emerging Technologies

Fully explore the potential of emerging technologies to reshape sustainable supply chains. Firstly, the "iron triangle" combination of 5G, blockchain, and the Internet of Things will inject new vitality into the supply chain. 5G ensures the high-speed transmission of massive data, the Internet of Things enables everything in the supply chain to be interconnected, and blockchain ensures the credibility and traceability of data. In the agricultural product supply chain, from environmental monitoring in the farmland planting stage, pesticide use traceability, to real-time temperature control in cold chain logistics, and then to product information query at the consumer end, the whole process is transparent and real-time shared, ensuring the green and safe quality of agricultural products and enhancing the overall resilience of the supply chain. This kind of reliable and transparent supply chain is crucial for ensuring food safety and sustainable consumption in Society 5.0.

Secondly, explore the application of artificial intelligence and robotics technology in the flexible production and rapid response of the supply chain. By using artificial intelligence to conduct deep learning on the changing trends of consumer demands, intelligent robot production lines can be driven to achieve rapid mold changing and personalized customized production, shortening the product delivery cycle. For example, in the clothing manufacturing industry, after consumers place orders, the intelligent factory can complete cutting, sewing, packaging, and delivery within 24 hours, reducing inventory backlogs, cutting carbon emissions, and meeting personalized market demands. This flexible and efficient production mode is in line with the personalized and on-demand production trends in Industry 5.0.

6.3. Optimization of Micro-Enterprise Decision-Making and Cultivation of Innovation Ecosystems

Focus on the micro-enterprise level to help enterprises optimize digital green innovation decisions. On the one hand, construct a refined cost-benefit evaluation model. Comprehensively consider multi-dimensional inputs such as technology introduction, talent cultivation, and equipment renewal, as well as long-term benefits such as energy conservation, waste reduction, and market expansion, to provide enterprises with accurate decision-making bases. Especially for small and medium-sized enterprises, help them find the balance point of input and output and stimulate their innovation motivation. This is crucial for enhancing the viability and innovation ability of small and medium-sized enterprises in Industry 5.0.

On the other hand, it creates an open and inclusive enterprise innovation ecosystem. Encourage cross-departmental collaboration within enterprises, establish innovation award funds to stimulate employees' innovation inspiration. At the same time, strengthen cooperation and exchanges between enterprises, establish industrial innovation alliances, share technology, talent, and market resources, form a synergistic innovation force, and promote the rapid diffusion of digital green innovation technologies within the industry. This kind of collaborative innovation environment is conducive to the overall development and upgrading of the manufacturing industry in the context of Industry 5.0 and Society 5.0.

6.4. Precise Guidance of Macro Policies and Regional Coordinated Development

The precise guidance of macro policies is of great significance for industrial development. On the one hand, formulate "one industry, one policy" and "one region, one policy" based on industrial characteristics and regional resource endowments. For example, for energy-intensive industrial agglomeration areas, increase subsidies for clean energy to guide enterprises to transform their energy structures; for regions rich in scientific research and development resources, set up special funds for digital green innovation to support cutting-edge technology research and development projects. This policy guidance is in line with the national and regional development strategies in the context of Industry 5.0 and Society 5.0, aiming to achieve sustainable development goals.

On the other hand, promote regional industrial cooperation and resource sharing. Build regional industrial cooperation platforms to facilitate the transfer of green manufacturing technologies and production capacities from the developed eastern regions to the central and western regions, realizing complementary advantages and common development among regions. For example, the Yangtze River Delta region exports new energy vehicle manufacturing technologies to the northern Anhui region, driving the upgrading of the local industry and alleviating the resource and environmental pressures in the eastern region, forming a coordinated development pattern across the country. This regional coordinated development is conducive to optimizing the overall layout of the manufacturing industry and promoting balanced development in line with the development trends of Industry 5.0 and Society 5.0.

6.5. Intelligent Green Production and Maintenance with Human-Machine Integration

Deeply explore the infinite possibilities of human-machine integration in intelligent green production and maintenance. On the one hand, develop a highly intelligent and humanized human-machine collaborative production system. Workers and intelligent robots work side by side. Robots complete difficult and repetitive tasks with precise manipulation, while workers use their creativity to solve complex process problems, improving production efficiency and product quality. For example, on the 3C product assembly line, human-machine collaboration has increased the assembly efficiency by 30% and reduced the product defect rate by 20%. This kind of efficient and high-quality production mode is in line with the requirements of Industry 5.0 for intelligent manufacturing.

On the other hand, a new model of green factory maintenance should be built based on a digital twin and remote operation and maintenance. By using digital twin technology to create a virtual model of the factory, it can reflect the operating status and energy consumption of equipment in real time. Engineers can perform remote monitoring and control, issue early warnings for maintenance, and optimize equipment operating parameters, reducing equipment downtime and energy waste, and realizing intelligent and green factory maintenance. This kind of intelligent and sustainable factory operation and maintenance is in line with the development needs of Industry 5.0 and Society 5.0, aiming to achieve efficient and low-carbon production.

7. Conclusions

Digital green innovation is at the core of the transition towards Industry 5.0 and Society 5.0, reshaping the manufacturing landscape with sustainable and intelligent solutions. By integrating advanced digital technologies such as artificial intelligence, blockchain, and the Internet of Things with green manufacturing principles, industries are achieving significant environmental, economic, and social benefits. These innovations drive carbon reduction, resource conservation, and waste minimization while simultaneously improving cost efficiency, productivity, and market competitiveness.

However, the research in this paper mainly focuses on the manufacturing industry, and pays less attention to the practices and achievements of digital green innovation in other industries such as agriculture and services. Moreover, the exploration of unpublicized practices of enterprises and failed transformation samples is still insufficient. Future research urgently needs to be supplemented and improved with cross-industry and cross-context longitudinal data.

Looking ahead, future research should emphasize interdisciplinary integration, leveraging quantum computing, nanotechnology, and biosciences to enhance green material development and precision manufacturing. Additionally, emerging technologies must be harnessed to optimize supply chains, foster micro-level decision-making, and create collaborative innovation ecosystems. Policymakers should provide tailored incentives to accelerate industrial transformation and regional development, ensuring a balanced and sustainable manufacturing sector.

Ultimately, the synergy of digitalization and green innovation will define the next era of industrial progress, where human-machine collaboration, intelligent production, and sustainable strategies will pave the way for a resilient, efficient, and environmentally responsible global economy.

Author Contributions

Conceptualization, Y.S., G.F.Y., Z.Q.Y. and J.N.N.; methodology, Y.S., M.L.J. and W.Y.L.; software, Y.S., G.F.Y., M.L.J. and W.Y.L.; validation, Y.S., Z.Q.Y., W.Y.L. and J.N.N.; writing—original draft preparation, J.N.N., Z.Q.Y. and Y.S.; writing—review and editing, J.N.N. and Y.S. All authors agreed to the manuscript.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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