Yang *et al. Green Manuf. Open* **2025**, *3*, 2
DOI: 10.20517/gmo.2024.120501

Green Manufacturing Open

Review

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Review: application of green manufacturing processes in precision machining of automotive components

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How to cite this article: Yang, Q.; Ming, W. Review: application of green manufacturing processes in precision machining of automotive components. *Green Manuf. Open* **2025**, *3*, 2. https://dx.doi.org/10.20517/gmo.2024.120501

Received: 5 Dec 2024 **First Decision:** 5 Feb 2025 **Revised:** 21 Feb 2025 **Accepted:** 28 Feb 2025 **Published:** 10 Mar 2025

Academic Editor: Zhichao Liu **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

Abstract

Green manufacturing technology is a key pathway for achieving sustainable development in modern manufacturing particularly in the precision machining of automotive components. This study provides a comprehensive overview of the core elements of green manufacturing, focusing on four key aspects: material selection, energy efficiency optimization, waste minimization, and recycling and remanufacturing. The review also examines the application of advanced technologies, such as laser machining and digital twins, in the green manufacturing process, highlighting their effectiveness through case studies of transmission gears and engine components. The results demonstrate that green manufacturing processes can significantly reduce energy consumption and waste generation, while improving material utilization and production efficiency. However, the high cost of equipment and the steep technical requirements remain significant barriers to widespread adoption. Looking forward, advancements in intelligence and digitalization are expected to drive further progress in green manufacturing, supporting the automotive industry's transition to a low-carbon future.

Keywords: Green manufacturing, automotive parts, precision machining, sustainable development, energy efficiency optimization

INTRODUCTION

As global demands for resource conservation and environmental sustainability continue to grow, the traditional manufacturing industry is encountering significant challenges. The integration of digital transformation and green technologies is reshaping the industrial landscape, fostering a path toward sustainable development focused on environmental protection and resource conservation. In sectors where energy consumption and resource utilization are concentrated, the adoption of digital and intelligent technologies is not only driving innovation but also steering the industry's future direction[1]. Green manufacturing represents both a technological frontier and an opportunity for the green transformation of the automotive industry, particularly in the precision machining of automotive components, a sector that consumes substantial resources and energy[2].

The growing societal demand for sustainability has intensified interest in sustainable manufacturing. Although this is an appealing goal for most, executives face significant challenges in its implementation, particularly in balancing social, economic, and environmental factors. These challenges are especially pronounced in highly competitive, consumer-oriented industries such as automotive manufacturing[3]. The intricate design and precision requirements of automotive components - such as transmission gears and engine parts - contribute to issues related to energy consumption and waste generation. Traditional machining methods, for example, are inefficient in energy use and generate significant amounts of metal scrap and hazardous waste, posing serious environmental risks[4]. Simultaneously, the increasing demand for green products and the tightening of environmental regulations are pushing manufacturing companies toward adopting green manufacturing technologies[5]. However, the technical challenge remains: how to reduce environmental impact while simultaneously improving processing efficiency and business outcomes.

This paper examines the application of green manufacturing in the precision machining of automotive components, aiming to promote the green development of the automotive manufacturing industry through improved material selection, optimized process paths, energy efficiency, and remanufacturing technologies. First, in terms of material selection, the study analyzes how environmentally friendly materials can reduce the environmental impact of the machining process. Since 1996, automotive manufacturers have increasingly opted for recyclable or biodegradable materials to minimize resource waste during processing[6]. Second, energy efficiency optimization is another key aspect of green manufacturing. This study evaluates the energy performance of various precision machining equipment, such as laser machining and microfabrication, and explores strategies to enhance productivity and resource utilization through advanced equipment and optimized machining paths[7]. Additionally, this paper investigates the implementation of scrap minimization and remanufacturing techniques. In terms of scrap minimization, the use of digital twin and simulation technologies has emerged as a significant trend in precision machining, allowing for precise control over cutting paths and times, thereby reducing scrap generation[7]. Remanufacturing technology, as part of the circular economy, offers an effective means to extend the life cycle of automotive components and reduce the environmental burden of end-of-life parts[8].

In the near future, the potential for applying green manufacturing in the precision machining of automotive components will be vast. The integration of green manufacturing with smart manufacturing opens up new possibilities for the green transformation of the automotive industry by further enhancing production efficiency and resource utilization. This paper examines the effectiveness of these approaches in energy optimization, waste control, and the circular economy, and explores the future direction of development through key technological elements, implementation methods, and real-world case studies. The aim is to provide both theoretical support and practical guidance for the industry's green transformation, offering specific and feasible paths for practitioners to navigate complex decision-making in sustainable manufacturing within the automotive sector[3].

OVERVIEW OF GREEN MANUFACTURING

Background

The concept of green manufacturing emerged in the 1990s, with the goal of reducing resource consumption and pollution emissions during the manufacturing process while promoting the efficient use of resources and environmental protection. Green manufacturing not only advances environmental protection technologies within the manufacturing sector but also plays a crucial role in enhancing the economic efficiency of enterprises and supporting sustainable development. In modern manufacturing, it has evolved from a theoretical concept to a practical application, particularly in resource-intensive industries such as automotive manufacturing, where the adoption of green manufacturing processes is especially critical[6].

Figure 1 illustrates the characteristics and methods of green manufacturing practices, which facilitate the transition to sustainability through smart, energy-efficient steps. Specific measures include reducing energy and water consumption, minimizing waste generation, and lowering emissions. Additionally, practices such as recycling, redesigning, and remanufacturing contribute to achieving sustainable manufacturing operations[9].

As China's environmental regulations and market demand for green products continue to strengthen, the industry faces an urgent need to explore the effective application of green manufacturing technologies. By integrating these technologies, manufacturers can maximize resource efficiency in the production process while minimizing environmental impact.

Environmental problems faced by processing of automobile parts and components

In the processing of automotive parts, environmental challenges are primarily concentrated in two areas: energy consumption and waste generation. On the one hand, energy consumption is a major issue. Processing of automotive components requires high-precision, complex equipment and processes, which consume substantial amounts of electricity and other forms of energy. According to statistics, the energy consumption of U.S. automotive companies exceeds 850 trillion joules per year. Traditional machining methods are not only energy-inefficient but also result in significant energy waste, driving up manufacturing costs and exacerbating environmental burdens[10]. On the other hand, waste generation is also a critical concern. As illustrated in Figure 2, conventional machining processes generate large quantities of waste liquids, metal shavings, and carbon dioxide[6]. If improperly managed, these waste products can severely harm the environment. For instance, metal shavings discarded carelessly can contaminate soil and water sources, while untreated waste liquids can pollute water bodies and ecosystems. Reducing waste generation and improving disposal practices through advanced machining technologies is crucial[11]. Addressing the issues of energy consumption and waste generation not only impacts the economic efficiency and social image of enterprises but is also a key factor limiting the sustainable development of the automotive industry.

KEY GREEN MANUFACTURING ELEMENTS IN PRECISION PROCESSING OF AUTOMOTIVE PARTS AND COMPONENTS

Green manufacturing in the processing of automotive parts consists of four key elements: material selection, energy efficiency optimization, waste minimization, and recycling and remanufacturing. In the context of global emphasis on resource conservation and environmental protection, these elements play a crucial role in supporting the greening and sustainability of automotive parts manufacturing[12].

Material selection

Material selection is an important starting point for green manufacturing, which directly affects the life

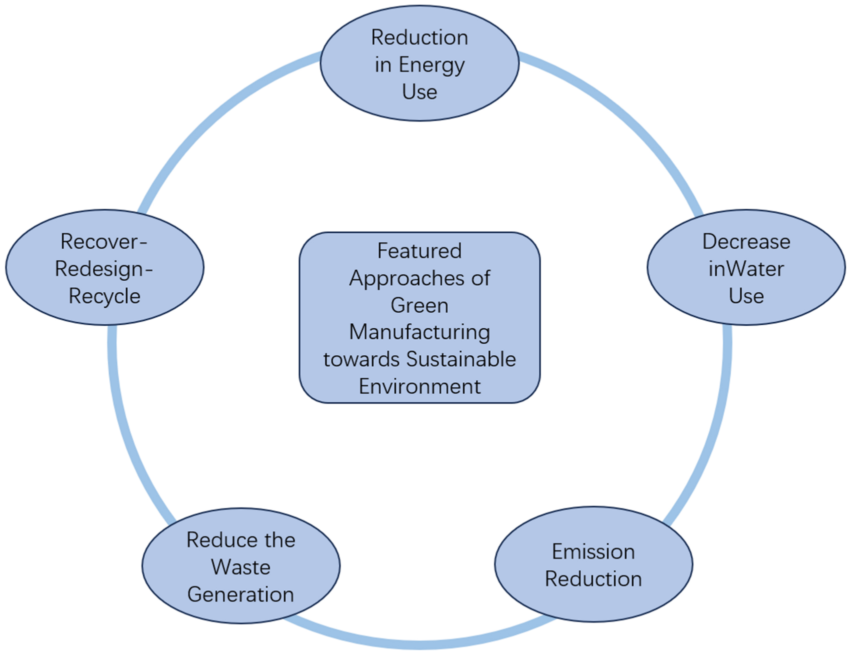

Figure 1. An important approach to sustainable green manufacturing[9].

cycle environmental burden of products. Traditional metal materials (e.g., steel and aluminum alloys) used in automotive parts manufacturing, despite their excellent mechanical properties, have a high energy demand during manufacturing and processing[13]. In addition, non-environmentally friendly materials are difficult to recycle and tend to increase the burden of waste disposal[14]. In recent years, green manufacturing has rapidly gained momentum worldwide. The design and manufacturing of automotive parts and components must align with this trend by optimizing material selection, ensuring the efficient use of resources and energy, and promoting cleaner production methods. These efforts will help reduce environmental impact and contribute to achieving sustainable development goals.

Aluminum alloys and high-strength steels

Chandel *et al.* have demonstrated that aluminum alloys and high-strength steels (HSS), commonly used in vehicle frames, offer superior recyclability and strength, significantly reducing the need for virgin materials. Meanwhile, rising fuel costs and stricter emissions standards have driven the automotive industry to produce lighter, more fuel-efficient vehicles. Aluminum-based hybrid composites have great potential to replace monolithic aluminum alloys and single reinforced composites in the lightweight, high-strength, high wear-resistant automotive field. The use of components made from lightweight alloys reduces the overall weight of vehicles, leading to significant fuel savings and further contributing to environmental protection[15].

In recent decades, there has been significant development in materials used for vehicle body construction, driven by the growing demands for performance and efficiency. Among the advancements in steel, various generations of HSS stand out. As shown in Figure 3, applying advanced high-strength steels (AHSS) can lead to a weight reduction of approximately 20%-30%. In addition to steel, lightweight alloys, particularly high-strength aluminum alloys, are increasingly being utilized. The weight reduction potential of aluminum alloys is even greater: compared to reference high-strength, low-alloy (HSLA) materials, the weight reduction achieved with aluminum alloys is typically in the range of 25%-40%[16].

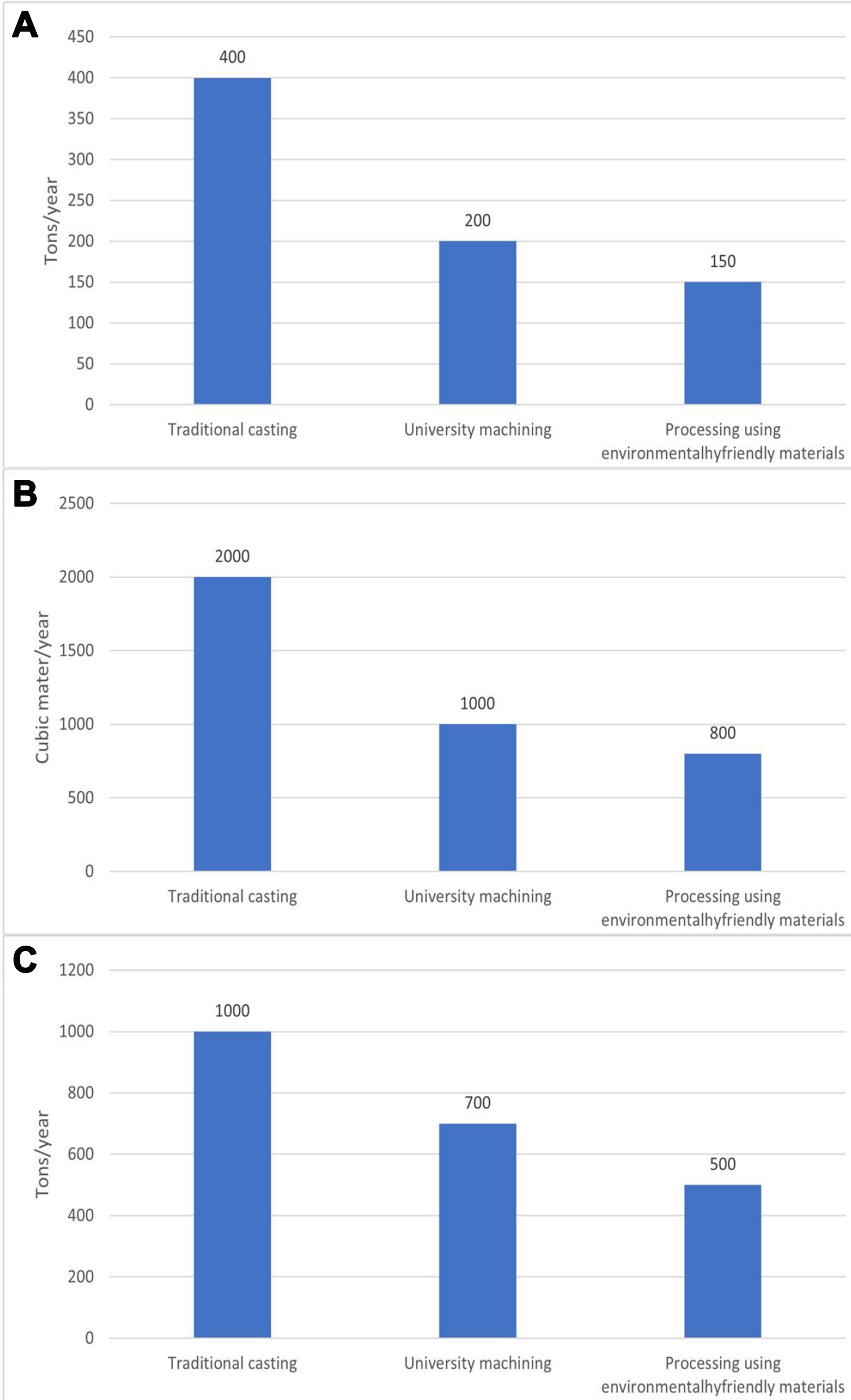

Figure 2. Generation and emission of various types of wastes. (A) Waste generation; (B) Wastewater discharge; and (C) Carbon dioxide emissions.

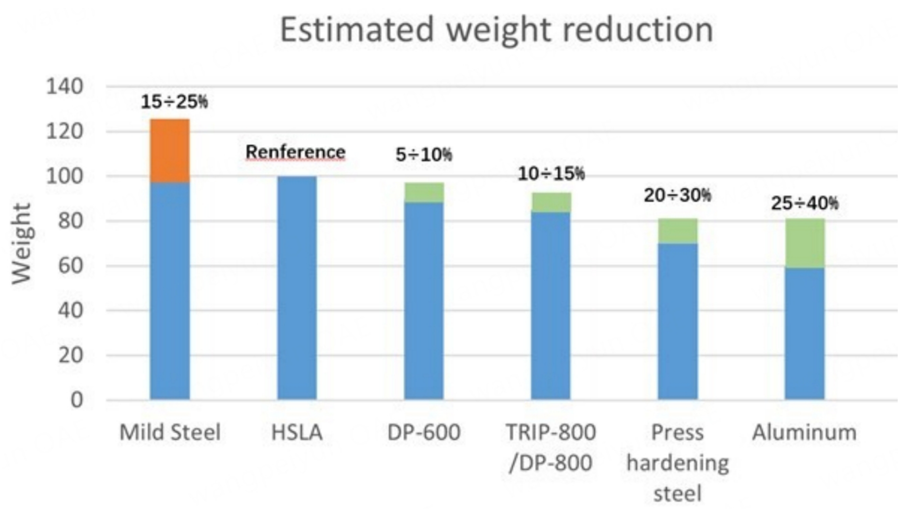

Figure 3. Estimated weight reduction for different materials[16].

In addition to the application of green manufacturing materials, technologies such as isothermal forging and additive manufacturing (AM) can be employed to improve material utilization and reduce processing waste. Isothermal forging offers several advantages over traditional stamping, including a more uniform temperature distribution across the cross-section of the forging, a lower strain rate of the metal (which reduces the deformation force), and a shape that is closer to the finished product, helping to save materials and improve product accuracy. These advantages align with the goals of green precision processing. Konstantinov *et al.* utilized a combination of computer simulation and isothermal forging technology to produce 5083 aluminum alloy "rack" components. The study results showed that the metal utilization rate of isothermal forging increased from 0.44 to 0.77 compared to conventional forging[17]. Similarly, He *et al.*, in their study of isothermal forging of AZ80 magnesium alloy support beams in a semi-closed die, found that the forged components had well-filled shapes, smooth surfaces, and good precision and material utilization[18].

AM is a process that builds solid components layer by layer, offering numerous advantages over traditional machining methods, including high design freedom, high forming efficiency, and improved material utilization. For example, in motors produced using AM, the high design freedom allows for a reduction in overall copper consumption by 15%, achieved by replacing the semicircular ends of conventional windings with right-angled ends[19]. Li *et al.* proposed a hybrid manufacturing process that combines arc AM [wire arc AM (WAAM)] and milling [hybrid WAAM and milling process (HWMP)], which demonstrated an increase in material utilization from 34% to 91% (a 57% improvement) in the machining of fascia boards, while also reducing construction time from 166 to 102 min (a 32% decrease)[20].

Carbon fiber-reinforced plastics

Composite materials, particularly carbon fiber-reinforced plastics (CFRP), offer numerous advantages, including light weight, high strength, high stiffness, excellent vibration resistance, fatigue resistance, and corrosion resistance. These properties make CFRP suitable for use in manufacturing body structures and components such as clutches. A reduction of 10 kg in vehicle weight improves fuel efficiency and leads to a decrease of 1g in carbon emissions. Table 1 provides a comparison of the weight of steel and CFRP. Compared to conventional steel frames, composite automotive frames offer twice the stiffness and flexural strength, while reducing weight by 50%[21]. As shown in Figure 4, global demand for CFRP composites has

Table 1. Comparison of the effect of replacing steel with CFRP on roof weight reduction[21]

Description	Weight
Steel roof	11.2 kg
Composite roof (CFRP)	5 to 5.5 kg
Weight reduction	6 to 6.6 kg

CFRP: Carbon fiber-reinforced plastics.

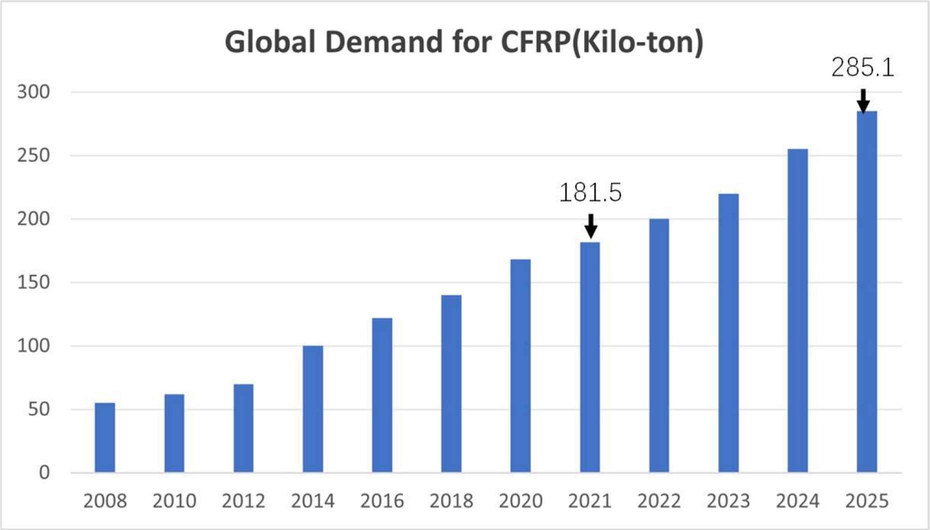

Figure 4. Global demand for CFRP composites from 2008 to 2025[22]. CFRP: Carbon fiber-reinforced plastics.

shown steady growth since 2014. In 2021, approximately 181 kt of CFRP was consumed - more than double the amount used in 2014. Demand is projected to reach 285 kt by 2025[22]. While CFRP materials are becoming more prevalent in automotive manufacturing, their high energy consumption during production and the need for further optimization of recycling technologies present ongoing environmental challenges.

The optimization of carbon fiber recycling technologies, such as pyrolysis recycling, relies on the principle of using high temperatures to break down the resin matrix by heating CFRP materials in an anoxic or low-oxygen environment, leaving behind pure carbon fibers. Typical pyrolysis temperatures range from 400 to 700 °C. However, conventional carbon fiber pyrolysis recycling has several drawbacks, including inefficient matrix removal, high energy consumption, fiber damage, and gas emissions[23]. Wei *et al.* proposed an improved pyrolysis recycling method that enhances matrix conversion and reduces energy wastage by optimizing factors such as temperature control, heating rate, nitrogen flow rate, and isothermal time. This method ensures fiber integrity by achieving efficient matrix removal with less than 1% carbon loss in the temperature range of 410-425 °C. By optimizing the heating rate (15 °C/min) and nitrogen flow rate (20 mL/min), surface corrosion and diameter shrinkage were minimized, while the tensile strength and tensile modulus of the recovered carbon fibers reached 80.3% and 87.6%, respectively, significantly improving the properties of the recovered fibers[24]. Additionally, Lopez-Urionabarrenechea *et al.* further advanced pyrolytic recycling by applying pyrolysis and oxidation to poly (benzoxazine) type CFRP wastes. This method effectively recovers high-quality carbon fibers, reduces surface damage, and increases the availability of the recovered fibers. They also employed waste materials (e.g., residual refractory) as solid bed materials during pyrolysis, which not only reduces costs but also increases the proportion of hydrogen (H_2) in the gas. By separating hydrogen gas and utilizing the high calorific value (HHV) by-product gas for power generation, the economics and sustainability of the pyrolysis process were improved. Moreover, the use of CSi-filled reactors significantly reduced liquid and waste generation during high-temperature heat treatment at 900 °C[25].

Natural fiber-reinforced composites

Traditionally, materials are selected mostly based on the experience of product design engineers and the materials readily available for common use. However, computer-based material selection has gained popular attention in recent decades[26]. One type of lightweight material used to promote sustainability in the automotive industry is natural fiber-reinforced composites. Replacing glass fibers with natural fibers reduces component weight due to the lower density of natural fibers (1.5 g/cc) compared to glass fibers (2.5 g/cc), while also increasing the renewable energy content of the vehicle. Many manufacturers incorporate these green fiber composites in non-structural and semi-structural applications, as illustrated in Table 2[27]. Ali *et al.* employed the analytic hierarchy process (AHP) with software tools to identify the most suitable natural fiber-reinforced composites by evaluating major criteria and sub-criteria in a hierarchical model. The final decision was based on sensitivity analysis of various scenarios, with a focus on environmental factors and sustainability. The results showed that hemp and polypropylene natural fiber composites ranked highest in the selection process and nearly met the requirements of industrial product design specifications, making them recommended materials for automotive component manufacturers implementing green technologies[26].

Energy efficiency optimization

Energy efficiency optimization is a core element of green manufacturing, particularly in high-energy-consuming processes such as processing. Processing equipment [e.g., computer numerically controlled (CNC) machines, laser machining systems] consumes large amounts of electricity during extended operations, making it essential to reduce energy consumption through the optimization of machining processes and equipment[28]. Recent studies, facilitated by advancements in CNC technology and intelligent control systems, have demonstrated that optimizing process parameters can significantly reduce energy consumption.

CNC machining (CNC)

The machining procedure is an important manufacturing process that is crucial for promoting sustainable production on the factory floor. One way to describe sustainable machining is as a machining process that can be maintained for a longer period of time while maintaining the same level of effectiveness. The social, economic, environmental, and technological aspects of the machining process are often preserved for a longer time frame to ensure sustainability[29]. Energy consumption optimization in CNC machining is advancing rapidly, with intelligent control technologies for real-time monitoring and management of equipment energy usage now being applied. The adjustment of machining parameters, such as feed rate, cutting speed, and depth of cut, has a direct impact on energy consumption and can be optimized to significantly reduce it. For example, optimizing feed rate and depth of cut can reduce tool wear while maintaining machining quality, thereby extending tool life and minimizing resource waste[30]. Studies have shown that energy consumption is directly proportional to cutting speed and tool wear, with feed rate having the most significant effect on both energy consumption and surface roughness[31]. Reducing cutting speed can lower overall energy consumption and decrease cutting temperatures, thereby reducing the need for coolant. In practice, fine-tuning processing parameters can optimize machining processes, enhance productivity, and reduce overall energy usage[29]. For instance, to minimize energy consumption during hole machining, an advanced cutting tool path and cutting parameter optimization method was proposed by Feng *et al.*[32]. The flowchart for optimizing turning machining to minimize energy consumption is shown in Figure 5.

Table 2. Examples of using green fiber composites[27]

Manufacturer	Model	NFC composite parts
Audi	A2, A3, A4, Avant, A6	Seat backs, side and back door panels, boot lining, hat track, and spare tire lining door panels, headliner
BMW	3, 5, and 7 series and others	Panel, noise insulation panels, seat backs, molded foot and well linings
Daimler/Chrysler	A,C, E, and S Class Evo Bus (exterior)	Door panel, windshield, dash board, business table, and pillar cover panel
FORD	Mondeo CD 162, FOCUS	Door panels, B-Pillar, and boot liner internal engine cover
Mercedes-Benz	Trucks	Engine insulation, sun visor, interior insulation, bumper, wheel box and roof cover
Toyota	Brevis, Harrier, Celsior, RAUM Golf, Passat,	Door panels, seat backs, and spare tire cover
Volkswagen	Variant, Bora, Fox, Polo	Door panels, seat backs, boot liner, and boot lid finish panel
Volvo	C70,V70	Seat padding, natural foams, and cargo floor tray

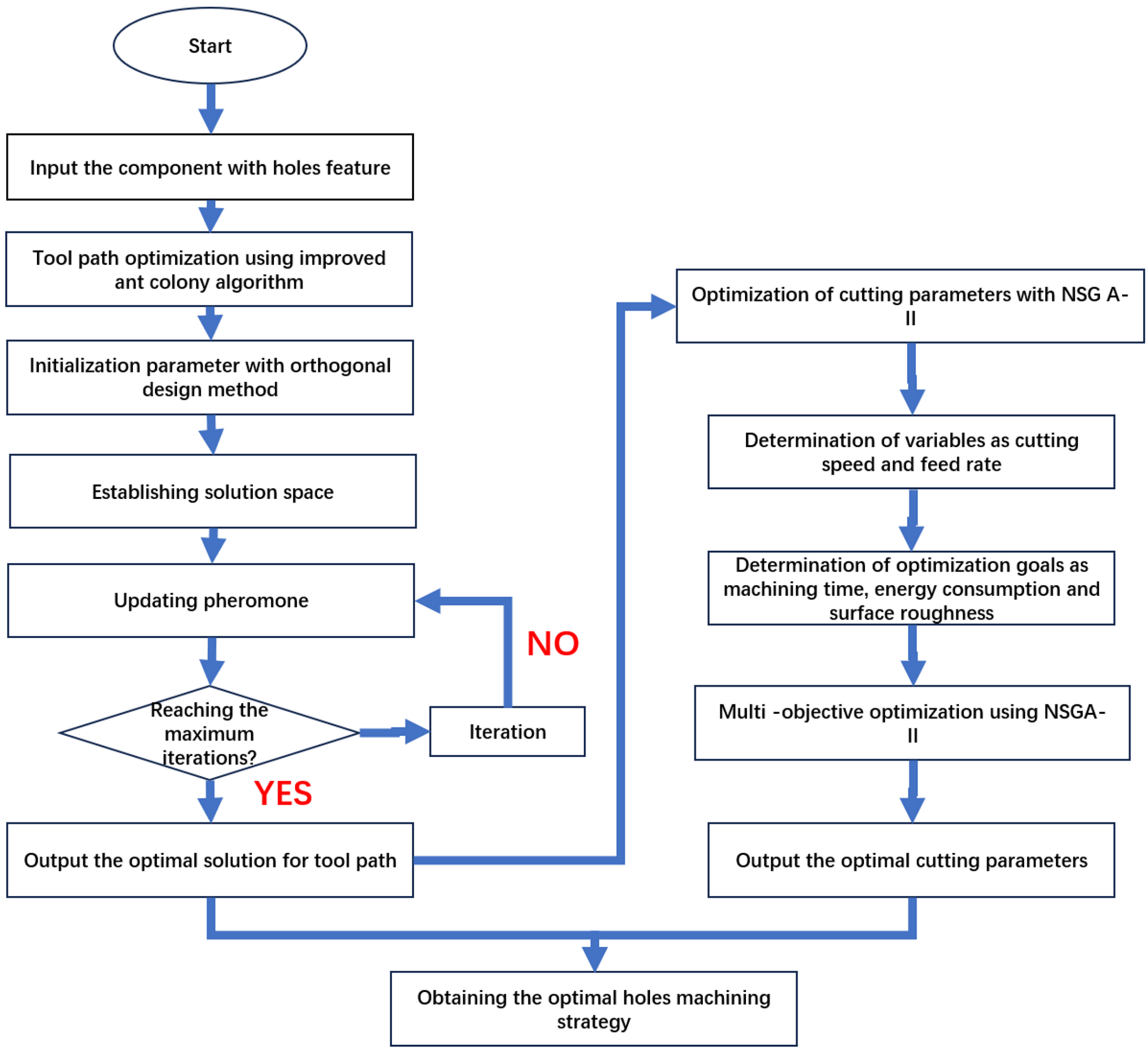

Figure 5. Turning process optimization to minimize energy use.

Micro-lubrication technology

One major factor contributing to energy wastage in machining is the friction generated during the movement of equipment, which results in heat production. Proper lubrication of machinery can lead to significant energy savings and plays a crucial role in reducing the operational costs of automotive parts manufacturing. Inadequate lubrication causes friction, which is an energy-consuming, wasteful, and often hazardous phenomenon[33]. Traditional lubrication methods are no longer sufficient for the demands of modern automotive parts processing, creating a need for more efficient alternatives. For instance, micro-lubrication technology, which has made considerable progress in recent years, is replacing conventional cooling and lubrication methods. Unlike traditional lubricants, which use large quantities of lubricant and generate waste liquid emissions, minimum quantity lubrication (MQL) requires only a small amount of lubricant to effectively reduce equipment wear and energy consumption[34]. Several studies have shown that MQL improves the permeability and wettability of droplets. Under positive charging conditions, the ferrite content of the workpiece's surface layer increases, while microhardness decreases, resulting in improved grinding performance[35]. In MQL machining, energy consumption values during CNC, spindle, and machining operations ranged from 612 to 972 kJ, respectively. The oil used in MQL reduces friction and chip pressure in the second zone of deformation, facilitating the production of shorter chips. As shown in Figure 6, the energy required to form chips in MQL machining is, on average, 21% lower than that in dry cutting. These results demonstrate that MQL machining is more energy-efficient[36].

Electrical discharge machining

Electrical discharge machining (EDM) is a manufacturing process that removes material from a workpiece by applying a series of electrical discharges between two electrodes. In gear manufacturing, it is particularly useful for machining complex gear geometries, especially those that are challenging to produce with traditional methods. EDM is capable of achieving precise tolerances, as small as one-thousandth of an inch, which is critical for the fatigue performance of gears. EDM-machined gears are known for their high accuracy and excellent surface finish. Figure 7 illustrates a typical wire EDM process for gear manufacturing[37].

Ming *et al.* highlighted that EDM requires attention to exhaust emissions due to the generation of harmful gases from thermal effects. To enhance green machining performance, it is essential to improve both energy efficiency and machining productivity while also considering ecological constraints. The concept of green manufacturing provides a framework for evaluating various aspects of the manufacturing process, though dynamically adjusting the weights of these aspects under real-world conditions remains challenging. They proposed a framework [Figure 8] for optimizing cutting parameters to minimize energy consumption and emissions across multiple materials in the EDM process[38].

Waste minimization

In processing of automotive parts, waste generation is inevitable; however, minimizing waste and ensuring its proper management remain major challenges in green manufacturing. The disposal of scrap not only leads to resource wastage but also poses significant challenges in waste management and environmental impact. One potential solution is green manufacturing, which can be achieved through the adoption of various technologies aimed at reducing waste and minimizing environmental pollution[39]. Waste reduction can be addressed both during the production process and in the final products.

A significant amount of waste is generated during manufacturing, but it can be reduced both in the production process and in the final product. The green manufacturing strategy for waste reduction is illustrated in Figure 9[12].

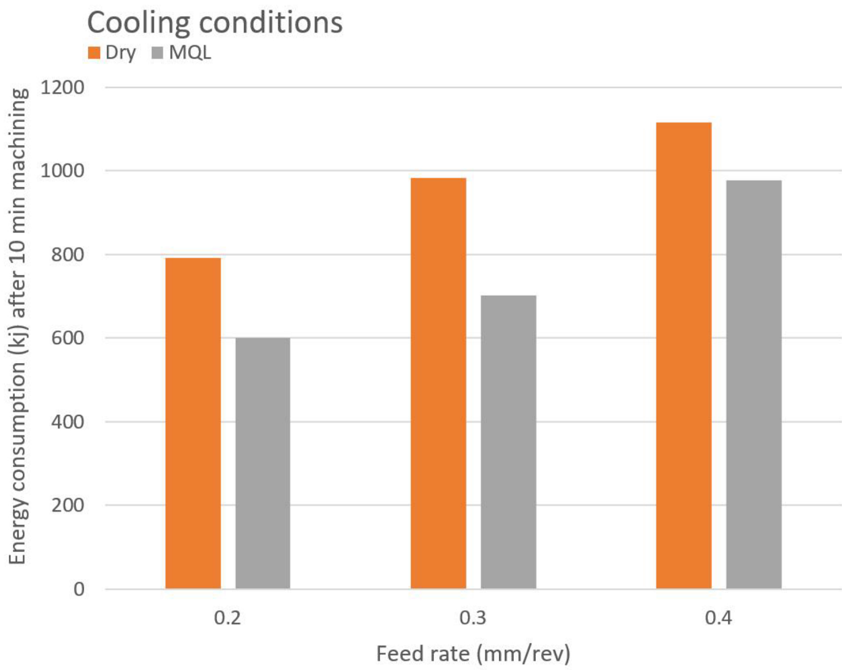

Figure 6. Processing energy under different conditions[36].

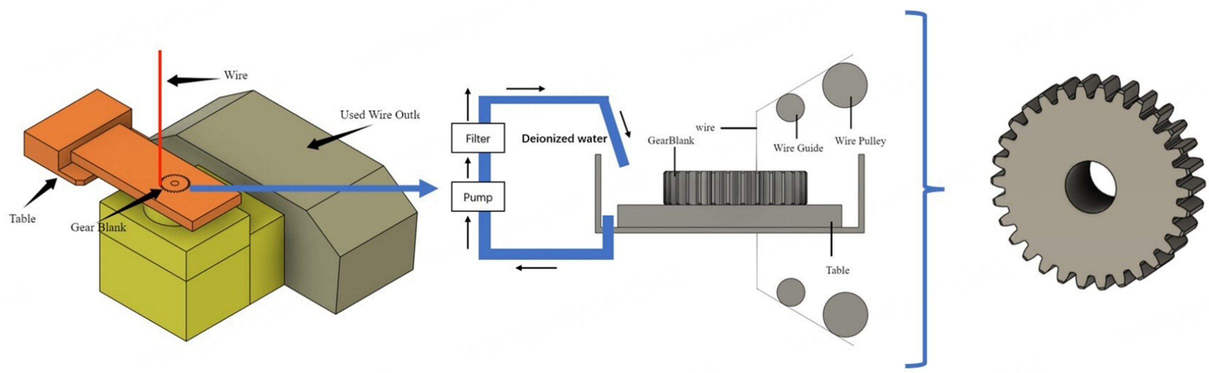

Figure 7. Schematic diagram of EDM wire cutting for machining gears[37]. EDM: Electrical discharge machining.

Reducing waste generation and improving material utilization through processing technology is a primary strategy in modern manufacturing[40]. The widespread adoption of CNC technology has made waste minimization increasingly achievable. This is primarily accomplished by optimizing machining parameters to reduce material waste and refining the cutting tool path to improve material utilization. An example of sustainable machining through process optimization in turning is shown in Figure 10. Additionally, the use of energy-efficient CNC machines and virtual simulation analysis further reduces energy consumption and identifies areas for process improvement. Collectively, these approaches minimize scrap, enhance process efficiency, and contribute to sustainable manufacturing, all while lowering operating costs and ensuring compliance with environmental regulations[29]. For instance, Eker *et al.* investigated the optimization of machining paths using simulation, adjusting parameters such as cutting speed, feed rate, and depth of cut to reduce material waste, improve machining accuracy, and ultimately achieve waste minimization[41].

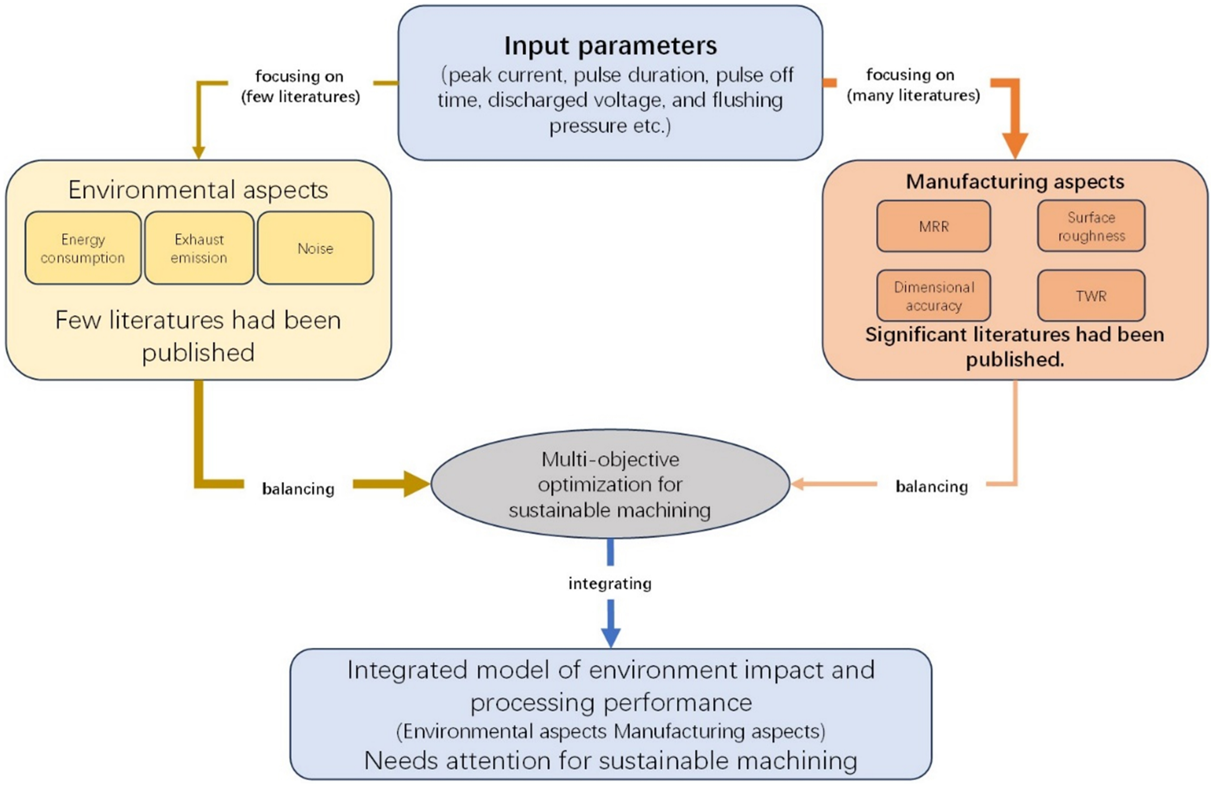

Figure 8. Sustainable processing of EDM processes in environment and manufacturing[38]. EDM: Electrical discharge machining.

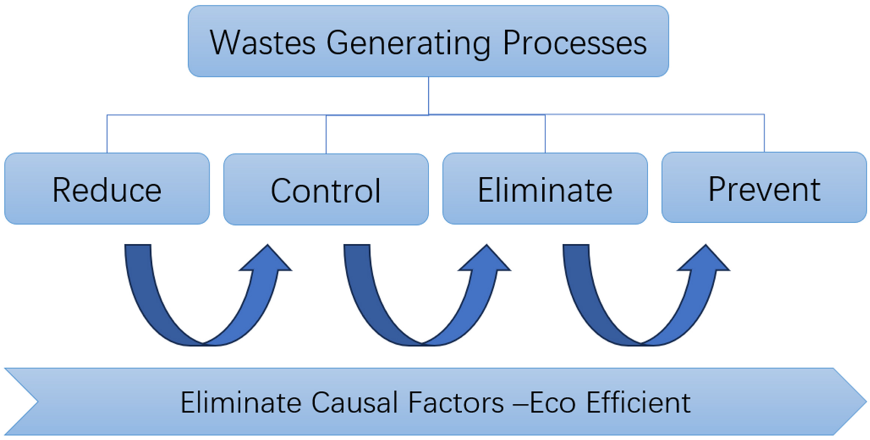

Figure 9. Green manufacturing strategies for waste reduction[12].

Advanced cutting and grinding processes play a crucial role in reducing scrap generation. Laser cutting technology, in particular, enables high-precision cutting and forming, leading to better material utilization and lower scrap rates. Studies have shown that scrap generation can be significantly reduced by optimizing parameters such as kerf width, kerf deviation, kerf angle, heat-affected zone (HAZ), weld slag formation, and surface roughness. Furthermore, optimization techniques, such as genetic algorithms, can be employed to improve cut quality and further reduce scrap, thereby enhancing material utilization. These optimization strategies contribute to more efficient material use while maintaining high cutting accuracy[42].

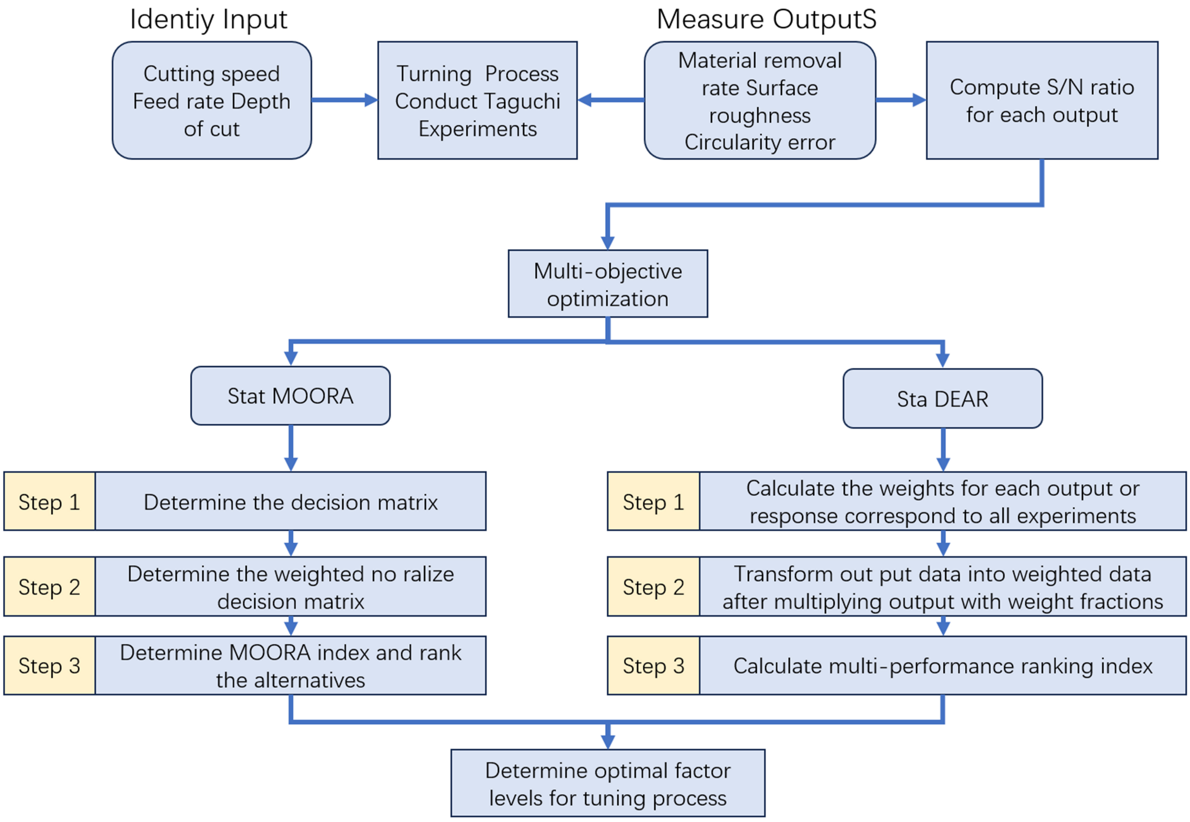

Figure 10. Turning process optimization.

Laser processing technology offers significant advantages in enhancing material removal rates and machining accuracy, particularly with its ability to localize light modulation in the sub-100 nm size range. This capability greatly improves material removal efficiency while minimizing waste generation. The technology holds substantial potential for processing of automotive engine parts, enabling the production of components with complex geometries. Moreover, it ensures efficient material utilization and reduces waste through precise control of the machining process, contributing to both cost control and environmental sustainability[43].

Recycling and remanufacturing

At the end of the manufacturing and lifecycle of automotive components, recycling and remanufacturing processes play a crucial role in achieving green manufacturing. These processes not only extend the service life of products but also help reduce the exploitation and waste of resources. The remanufacturing process typically involves steps such as cleaning, repairing, and inspecting, which restore used parts and components to a functional state similar to the original[44,45].

The material input, energy consumption, and value-added parameters for remanufacturing and direct reuse are presented in Table 3. Liu *et al.* investigated the uncertainty associated with changes in resource productivity induced by these processes. Uncertainty in remanufacturing and direct reuse was modeled separately, with each process being analyzed independently by setting the other process rate to zero, thus isolating its effect. The results indicate that both remanufacturing and direct reuse have positive effects, even though the maximum uncertainty in the change in resource productivity may reach up to 22%[46].

Table 3. Materials input, energy consumption and value added of remanufacturing and direct reuse compared to manufacturing new products[46]

	Materials input	Energy consumption	Value added
Remanufacturing	32% ± 22%	25% ± 7%	80% ± 22%
Direct reuse		13% ± 4%	54% ± 18%

Studies have shown that remanufacturing used automotive parts can result in significant resource and energy savings. Remanufactured automotive engines, for instance, require up to 83% less energy, produce up to 87% fewer CO_2 emissions, use 92% fewer chemical products, generate 70% less waste, and require more than 90% less raw material compared to newly manufactured engines[47,48] [Table 4]. For example, in the remanufacturing of transmissions and engines, parts can be restored to full functionality through cleaning and surface treatment. The cost of a remanufactured part is typically only about 50% of the cost of a new one[49]. Additionally, recycled metals such as aluminum and steel can be reintroduced into the production process via smelting, significantly reducing the demand for new materials[50].

The development of new energy vehicles (NEVs) has become a significant trend, and the recycling and remanufacturing of power batteries for NEVs plays a crucial role in achieving a closed-loop system for resource use. Common processing methods for NEV power batteries include:

Graduated Utilization: Retired batteries, typically with 70%-80% of their original capacity, are repurposed for use in energy storage systems (e.g., home energy storage, grid peaking) after undergoing precision testing and restructuring. This process can extend the battery lifespan by five to eight years[51].

Material Regeneration: Metals such as cobalt, nickel, and lithium are extracted through a combined pyro-wet process, achieving recovery rates of 95%, 90%, and 85%, respectively. This method is exemplified by Belgium's Umicore process[52]. Similarly, Redwood Materials uses a pyro process to recover nickel and cobalt alloys with a purity of over 99% and extracts lithium through a wet process, achieving a recovery rate above 80%. Their goal is to reduce the carbon footprint of battery materials by 70% by 2030.

Direct Repair Technologies:
Electrochemical Lithium Replenishment: This method repairs the solid electrolyte interface (SEI) film of the negative electrode by electrolyte injection and *in-situ* lithium deposition, restoring battery capacity to 92% of its initial value[53].

Laser Repair of Electrodes: Femtosecond lasers are used to remove surface degradation layers, such as lithium dendrites, with micron-level precision, avoiding the need for complete disassembly of the battery[54].

These advancements in battery recycling and remanufacturing are critical to enhancing the sustainability of NEVs and significantly reducing the environmental impact of battery production and disposal. Table 5 shows a comparison of mainstream recovery processes (thermal, wet, direct remediation).

In recent years, smart manufacturing and Internet of Things (IoT) technologies have increasingly contributed to the remanufacturing process. By tracking and monitoring the usage and remaining life of parts, manufacturers can better manage and plan remanufacturing operations. IoT, in particular, enables real-time scheduling of automotive engine remanufacturing, thereby improving resource management efficiency[55]. The Battery Passport developed by IBM uses digital twins and blockchain to record battery

Table 4. Assumptions about material, energy and water use in remanufacturing compared to the base case[46]

Remanufactured parts	Base-case [new/rem]	Scenario min [new/rem]		Scenario max [new/rem]	
Al [kg]	30.0	2.1	27.9	10.0	20.0
Bronze [kg]	0.2	0.2	0.0	0.2	0.0
EPDM [kg]	0.2	0.0	0.2	0.2	0.0
Iron[kg]	68.6	1.6	67.0	10.8	57.8
PA66 [kg]	0.5	0.1	0.4	0.5	0.0
PP [kg]	0.5	0.4	0.1	0.5	0.0
Rubber [kg]	0.7	0.6	0.1	0.7	0.0
Steel [kg]	50.0	7.1	42.9	28.3	21.7
Tin [kg]	0.1	0.1	0.0	0.1	0.0

Table 5. Comparison of mainstream recovery processes

Process type	Energy efficiency (kWh/kg)	Metal recovery rate (%)	Carbon footprint (kg CO_2/kg)
Pyrometallurgy	8-12	Co > 95, Ni > 90	10-15
Hydrometallurgy	5-8	Li > 85, Co > 98	6-10
Direct Repair	2-3	Capacity restoration > 90	1-2

lifecycle data (e.g., charge/discharge counts, health status) to guide efficient dismantling and material sorting[56]. This not only enhances the efficiency of recycling and remanufacturing, but also strengthens the traceability of parts recycling[57].

IMPLEMENTATION METHODS OF GREEN MANUFACTURING PROCESSES

Advanced processing technology

In the field of green manufacturing, the application of advanced processing technologies is crucial for achieving resource conservation and environmental sustainability. Among these, laser processing and microfabrication technologies are particularly emphasized due to their high precision and efficiency.

Laser cutting and laser welding can be applied to the precise processing of vehicle body components, effectively reducing material waste and energy consumption compared to traditional machining methods. For instance, laser welding is particularly suitable for the accurate joining of thin metal sheets, minimizing the need for cooling fluids. By optimizing laser power and processing parameters, energy consumption can be further reduced. Kravchenko *et al.* explored the sustainability benefits of laser processing in manufacturing, highlighting its potential to minimize material use and waste generation[58].

Micromachining technologies, such as micro EDM and micro milling, are essential for the high-precision fabrication of components, such as engine parts and miniature components in transmission systems. These technologies offer precise machining capabilities while reducing material waste, particularly in the production of parts requiring extremely tight tolerances. Additionally, they contribute to minimizing environmental impact[59].

Conventional coolants often contain hazardous chemicals that pose risks to both the environment and operator health. In contrast, advanced machining technologies typically require less coolant, thereby reducing the challenges associated with the disposal of environmentally harmful coolants[60]. These technological advancements not only enhance productivity but also contribute to a green transformation in manufacturing. Kui *et al.* demonstrated that the application of MQL technology significantly reduced

 Yang *et al. Green Manuf. Open* **2025**, *3*, 2 | https://dx.doi.org/10.20517/gmo.2024.120501

coolant usage by employing very small amounts of lubricants and coolants. This trace amount of lubricant is typically delivered as a mist to the cutting area, reducing coolant consumption by more than 90% compared to conventional methods[61]. Furthermore, in titanium turning, the use of ionic liquid-based MQL improved tool life by 60%, and up to 88% under specific conditions[60], effectively reducing tool wear. Table 6 presents a comparative analysis for cooling/lubrication technologies.

By optimizing laser processing parameters, energy consumption and waste generation can be significantly reduced[62]. Due to its excellent efficiency and accuracy, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was selected by Ma *et al.* as a model for solving the multi-objective optimization energy prediction problem in laser machining. The flowchart of the coding scheme for NSGA-II is shown in Figure 11. The energy prediction model helps in selecting appropriate processing parameters, thereby improving energy efficiency. Experimental results demonstrated that the model provided reliable power predictions under new sintering conditions, significantly reducing energy consumption and waste generation[63]. These studies suggest that by adopting and optimizing such technologies, manufacturing can move toward greater sustainability.

Computer-aided manufacturing

The use of computer-aided manufacturing (CAM) software in green manufacturing is primarily driven by its ability to optimize process paths, thereby reducing energy consumption and material waste. By simulating the machining process, CAM software enables engineers to evaluate different machining strategies and select the most energy-efficient and waste-reducing methods[64]. For example, CAM software can optimize cutting paths, minimize idle strokes on the machine, and enhance cutting efficiency, resulting in lower energy consumption[64]. Additionally, for the machining of complex components, such as engine assemblies and body parts, CAM software can also simulate and optimize cutting parameters, including cutting speed, feed rate, and cutting depth, to reduce energy consumption and tool wear during the manufacturing process. This optimization maximizes material utilization and minimizes waste[65].

Another important application of CAM software is in lean manufacturing, which is facilitated by its ability to optimize material use. By precisely controlling material consumption, CAM software helps reduce scrap and improve material utilization. For example, Kumar *et al.* explored the use of CAM software to optimize cutting paths, demonstrating how energy consumption and scrap generation can be reduced by minimizing cutting distance and optimizing cutting parameters[66]. These studies highlight the role of CAM software as a critical tool in green manufacturing, providing strong support for the sustainable development of the manufacturing industry by optimizing process paths and minimizing resource wastage[67].

Digital twins and simulation

Digital twin technology, which has emerged in recent years within the manufacturing industry, involves the use of digital twin models to simulate the entire manufacturing process, from raw materials to finished products. In automotive manufacturing, digital twin technology can replicate the entire production line, allowing for the simulation of the manufacturing process from start to finish. Through virtual simulations, it is possible to predict and optimize energy consumption and waste generation during production, helping companies select more environmentally sustainable manufacturing solutions. This capability enables manufacturers to identify potential issues and optimize systems for improved performance[68]. In the context of green manufacturing, digital twin technology can be used to simulate processes and assess the effectiveness of sustainable manufacturing solutions. By simulating machining processes in a virtual environment, engineers can predict and optimize energy consumption, waste generation, and environmental impacts before actual production begins[69]. Kamble *et al.* proposed a sustainable digital supply chain twin framework [Figure 12][70]. Their study demonstrates that the digital supply chain twin

Table 6. Comparative analysis of cooling/lubrication technologies

Comparative dimensions	Conventional cast cooling	MQL technology	Cryogenic cooling
Cooling media	Mineral-based emulsions (with chlorine/sulfur additives)	Vegetable oil-based/ionic liquids (biodegradable)	Liquid nitrogen/carbon dioxide
Consumption (L/h)	20-50	0.05-0.2	5-8 (phase change cycle)
Specific energy consumption (kWh/kg)	0.8-1.2 (including waste liquid treatment energy consumption)	0.3-0.5 (compressed air drive)	1.0-1.5 (low temperature preparation)
VOC emission (g/m^3)	120-200	15-30	< 5
Tool life improvement	Baseline values	60%-88% (titanium alloy)	40%-70% (nickel-based alloy)
Applicable scenario	Heavy duty roughing	Finishing/difficult materials	High temperature alloys/composite materials

MQL: Minimum quantity lubrication.

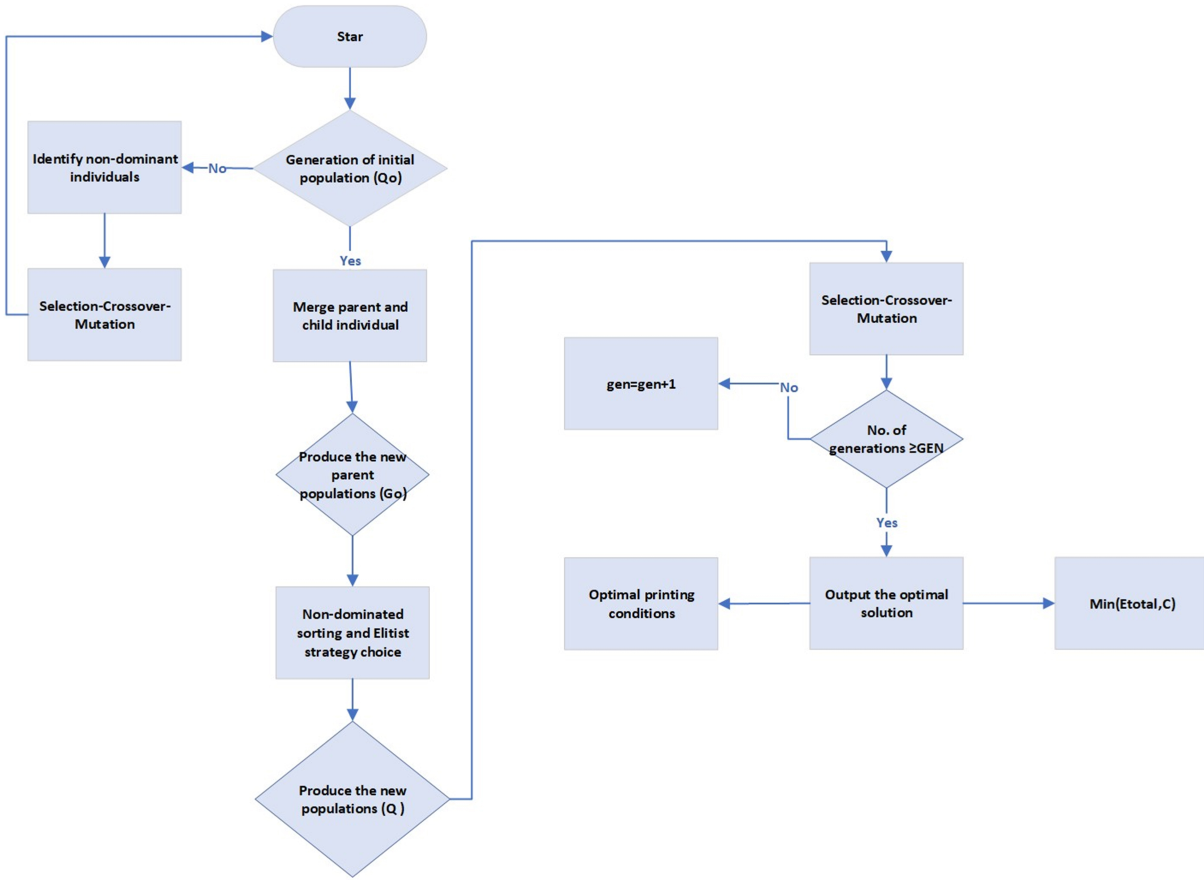

Figure 11. Flowchart of the optimized NSGA-II coding scheme[63]. NSGA-II: Non-dominated Sorting Genetic Algorithm II.

facilitates the aggregation, integration, and dynamic allocation of manufacturing resources, enabling the effective integration of networks and improved resource management for greater supply chain sustainability[70].

The integration of digital twin technology with simulation software offers a powerful platform for green manufacturing. It enables manufacturers to test and implement more sustainable strategies without compromising productivity. For example, in their study, Chen *et al*. demonstrate how digital twins can be

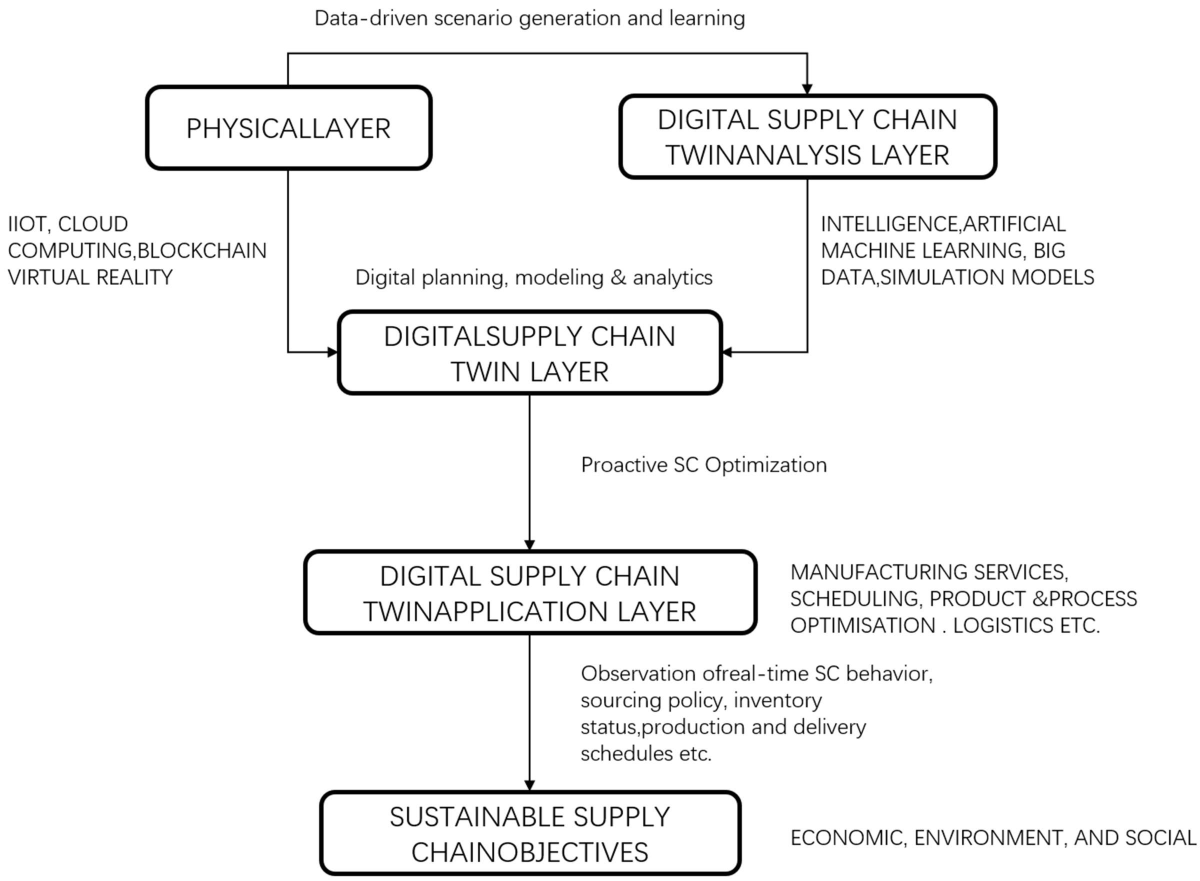

Figure 12. Sustainable digital supply chain twin implementation framework[70].

used to optimize manufacturing processes, reducing energy consumption and waste generation[71]. Additionally, digital twin technology can be integrated with IoT devices to monitor and adjust the production process in real time, further enhancing sustainability[72,73]. By analyzing data from IoT devices, digital twins can predict and optimize energy and material use during production, leading to more efficient resource utilization[68].

The application of digital twin technology extends beyond individual machines or processes and can be applied to entire factories or supply chains. By simulating and optimizing production processes on a larger scale, digital twins can support the green transformation of the entire manufacturing system. Their use throughout the lifecycle facilitates information sharing, enables technology exchange, improves design quality, reduces design errors, enhances energy use and efficiency, supports rapid implementation, and lowers carbon footprints[74]. In their study, Leng *et al.* explored the potential of digital twin technology in optimizing entire production systems, demonstrating how dynamic resource allocation and supply chain management can help automotive manufacturers reduce costs and minimize environmental impact[75].

CASE STUDY

Transmission gear

Transmission gears are critical components in the automobile powertrain, and their quality and manufacturing precision directly influence transmission efficiency, driving experience, and fuel economy. With growing global concerns about environmental protection and sustainable development, green manufacturing technologies have become a key focus in the automotive industry. Traditional gear processing requires substantial material and energy inputs and generates significant waste[37]. The traditional machining process is illustrated in Figure 13. Green manufacturing seeks to reduce resource consumption and waste generation by optimizing design and production processes, thus contributing to environmental sustainability. Processing, an essential process in gear production, is widely used to enhance the accuracy and performance of transmission gears. The greening of processing typically involves reducing energy consumption during cutting, using environmentally friendly coolants, and improving material utilization throughout the machining process.

Green manufacturing technology can be applied in various aspects of the transmission gear production process, including the following:

(1) Transmission gear processing technologies, including milling, grinding, and gear cutting, improve gear accuracy but also lead to higher energy consumption and waste generation. Factors influencing energy consumption during gear processing are shown in Figure 14. To mitigate these negative impacts, modern manufacturing companies have adopted several green processing methods. First, the use of low-energy, high-efficiency machining equipment can significantly reduce energy consumption. Second, when selecting cutting fluids, many companies are increasingly opting for environmentally friendly options or MQL technology. These alternatives not only reduce pollutant emissions but also effectively extend the service life of cutting tools and improve machining quality[76].

One of the most noticeable effects of green manufacturing technology in transmission gear production is the significant reduction in energy consumption. For instance, optimizing the cutting process and using low-energy equipment has improved energy efficiency during production. According to one study, the energy consumption of a gear production line was reduced by approximately 20% through the use of high-efficiency motors and intelligent regulation systems[77,78]. Additionally, the optimization of coolant and lubrication technologies reduces both the frequency of coolant recycling and disposal challenges, further lowering energy consumption in production[37].

(2) Material selection plays a crucial role in the manufacturing of transmission gears. Traditional gear materials, such as high-alloy steels and other high-performance materials, are produced and processed with high energy consumption and waste generation. Therefore, the optimal selection and recycling of materials are critical in green manufacturing[79]. For example, vehicle power transmission components are often made from metal matrix composites (MMCs), which incorporate wires, whiskers, or particles of high-strength materials to enhance the matrix's properties in critical areas. In the medium term, more advanced solutions may involve the use of polymer matrix composites (PMCs)[80]. Additionally, the application of powder metallurgy technology in gear manufacturing can reduce material waste and improve material utilization[81].

Studies have shown that the material utilization of transmission gears can be increased by approximately 15%-30% through the use of powder metallurgy technology and optimized material processing techniques[1,82]. Additionally, the use of composite materials and lightweight design not only reduces material consumption but also enhances product performance and durability, further advancing the automotive industry's shift toward green manufacturing[83].

(3) With the advancement of Industry 4.0, automation and intelligent production technologies have gradually become central to the manufacturing industry. The production of transmission gears is no exception, as the use of robots, intelligent production lines, and IoT technology not only enhances

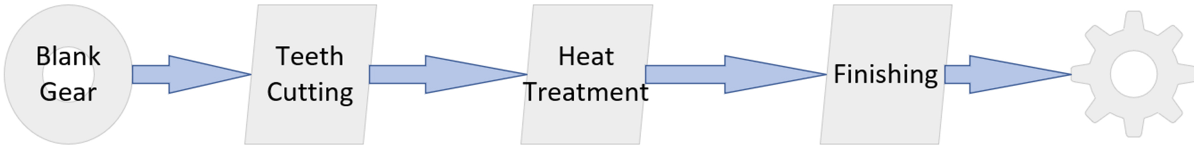

Figure 13. Typical processes for machining gears.

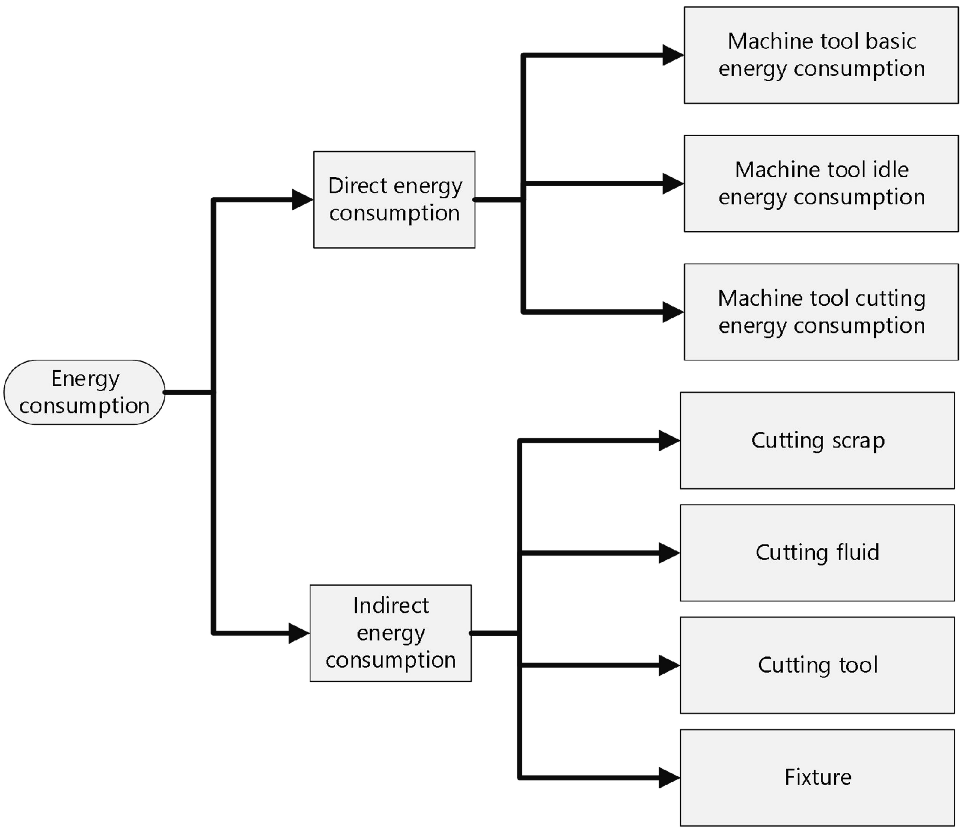

Figure 14. Factors affecting energy consumption of gear processing.

production efficiency but also optimizes energy use throughout the production process[84,85]. For instance, real-time monitoring systems that dynamically adjust energy consumption can help maintain product quality while minimizing unnecessary energy waste[86].

(4) Green manufacturing requires companies to adopt measures that reduce waste generation. In transmission gear production, waste primarily consists of cutting chips, used tools, and waste gases and liquids generated during the machining process. By optimizing processing technologies and improving process workflows, waste generation can be significantly reduced. For cutting chips and other waste materials, some companies mitigate environmental pollution by recycling and reusing them as raw materials[87]. This approach not only supports environmental objectives but also enhances the economic efficiency of the organization[88].

By optimizing the production process and minimizing unnecessary cutting and grinding, the amount of waste generated during gear production has been substantially reduced by 22 percent[37]. Additionally, waste recycling has become a key practice within the industry. Several studies have demonstrated that waste generation from gear production has been reduced by approximately 25% through the use of precision cutting techniques and waste recycling practices[89].

Engine

As global environmental challenges become increasingly severe, the automobile manufacturing industry is confronted with both unprecedented challenges and opportunities. As a core component of automobiles, the engine manufacturing process plays a crucial role in influencing energy consumption, material use, and waste generation across the entire industry[90]. Green manufacturing technologies have emerged as a key strategy in engine production, aimed at reducing environmental impact and enhancing resource utilization. This section reviews the application of green manufacturing technologies in the processing of engine components and analyzes their effects on energy consumption, material utilization, and waste generation[91,92].

The core of green manufacturing technology lies in energy saving, emission reduction, and the efficient utilization of resources throughout the entire product design and manufacturing process. Processing of engine components is complex and requires high precision, often involving energy-intensive processes such as casting, cutting, and heat treatment. Therefore, the implementation of green manufacturing technologies in processing is of great importance. Key measures include the use of high-efficiency equipment, optimization of process flows, integration of digital technologies, and the selection of environmentally friendly materials[93].

In engine manufacturing, the implementation of green manufacturing technologies is primarily reflected in the following aspects:

(1) Engine components (e.g., cylinder blocks, pistons, connecting rods, crankshafts, and turbochargers) typically require high-precision processing. By integrating intelligent machining centers and energy-efficient machine tools, both productivity can be improved and energy consumption per unit of product can be significantly reduced. Figure 15 shows the resulting flow rates for three methods compared to the reference setup of the exemplary machining process (with constant pressure control)[94]. For the reference process, adjusting the flow rate resulted in a 12% reduction in pump power. Using the simulation-based approach, the energy demand of the high-pressure pump was reduced by 81%, leading to a total energy saving of up to 37% for the entire machine tool[94].

(2) The cutting process typically requires a large amount of coolant and lubricants, which can be potentially harmful to the environment[95]. In recent years, MQL technology and dry machining have been increasingly applied in the manufacture of engine components. MQL technology achieves effective cooling of the cutting tool by spraying a small amount of vegetable-based lubricant, reducing the need for coolant and minimizing the waste liquid generated during the cutting process.

The adoption of green manufacturing technologies significantly reduces energy consumption in machining processes. For instance, a study demonstrated that the use of high-efficiency machining centers reduced the unit energy consumption of engine parts by 20%-25%. Furthermore, optimizing the heat treatment process led to an increase in energy efficiency by more than 10%[96].

(3) The application of lightweight materials, such as aluminum alloys, magnesium alloys, and composite materials, is becoming increasingly common in engine manufacturing. These materials not only reduce

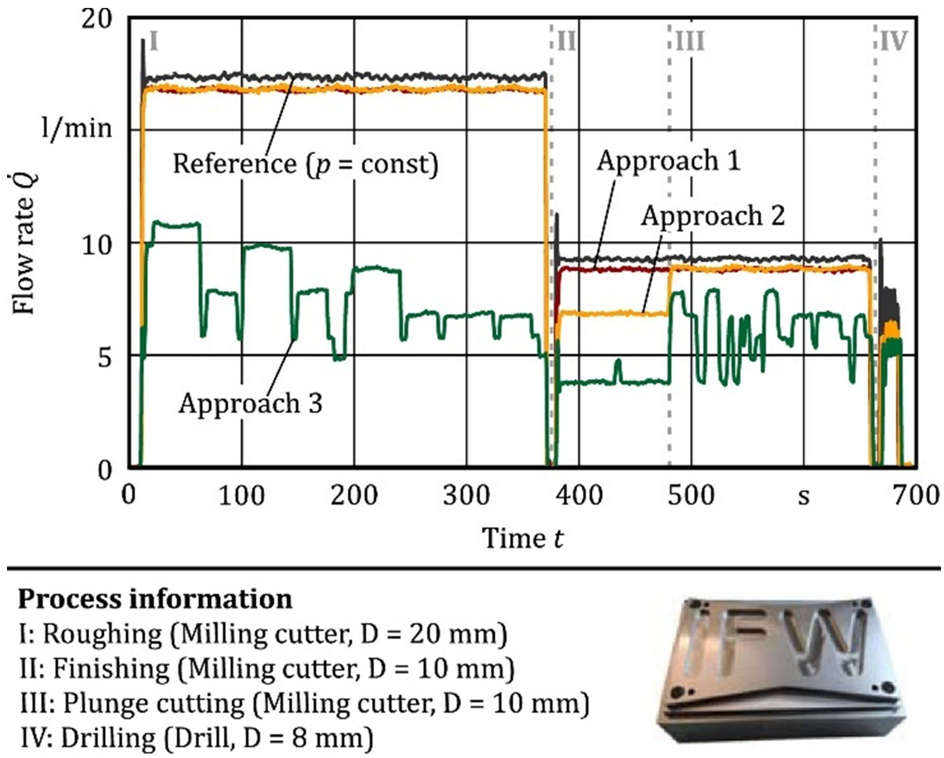

Figure 15. Flow rates for different methods of adaptive cutting fluid application[94].

engine weight but also improve material recycling rates. For example, one study demonstrated that replacing conventional cast iron with aluminum alloys for cylinder heads can reduce material weight by approximately 30% and significantly improve fuel economy[97]. Additionally, the use of powder metallurgy to produce engine parts maximizes material utilization and reduces scrap[98].

The introduction of lightweight materials and powder metallurgy technology has significantly improved material utilization in engine manufacturing. For example, powder metallurgy allows for material utilization rates exceeding 95%, while traditional processes typically achieve only 60%-70% efficiency[98].

(4) Zhang *et al.* extended the Ma Trace model and used it to quantify the impact of engine remanufacturing on reducing metal losses. The structure of the extended Ma Trace model is shown in Figure 16[99]. Through a 50-year case study, they found that extending the service life cycle of a product through remanufacturing reduced the overall physical loss of steel, nickel, and chromium in vehicle engines by 3%, 2%, and 5%, respectively, compared to a scenario where all used products are recycled. These results quantitatively demonstrate the advantages of engine remanufacturing over material recovery in minimizing material dissipation within a circular resource system[99].

(5) The application of digital technology in green manufacturing has become a growing trend. Through real-time monitoring and data analysis of the manufacturing process, energy usage can be optimized, and unnecessary processing operations can be minimized[100]. For example, intelligent control of machine tools using IoT technology allows for dynamic adjustment of power output, thereby reducing energy consumption. Additionally, digital simulation technology is widely used in the process design of engine parts, helping to minimize resource waste during the trial production stage[101].

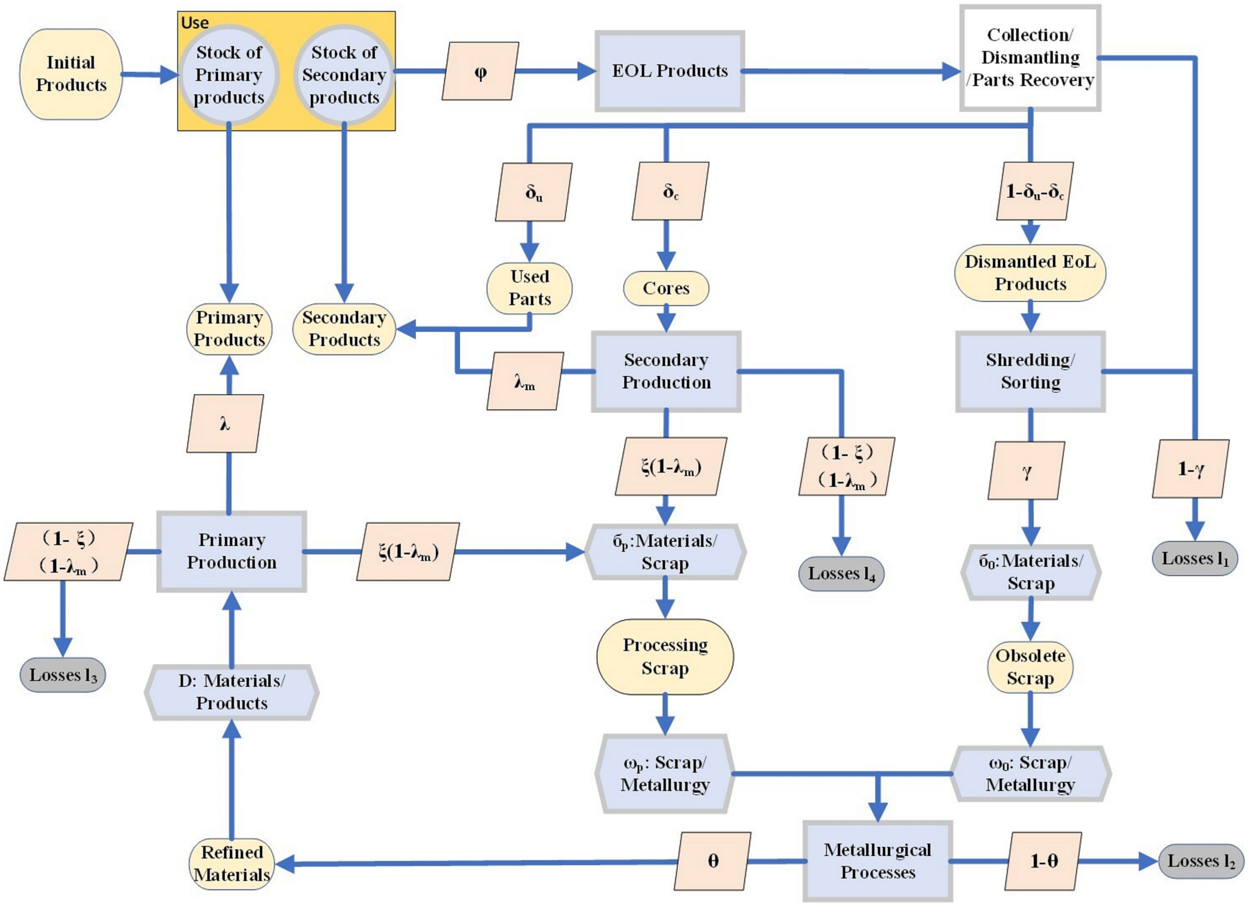

Figure 16. Structure of the extended Ma Trace model[99].

(6) The large amounts of waste, such as swarf, waste liquids, and exhaust gases, generated during the engine manufacturing process, pose significant environmental concerns. The environmental impact of this waste can be effectively reduced by improving recycling processes and waste treatment technologies[102]. For instance, the use of advanced filtration equipment to regenerate coolant not only extends its service life but also reduces the discharge of waste liquids[103].

Electric vehicle batteries

Electric vehicle (EV) batteries are crucial components in the transition to sustainable transportation. Their design and manufacturing processes significantly influence environmental sustainability and overall efficiency. As global attention increasingly focuses on reducing carbon emissions and resource consumption, the implementation of green manufacturing technologies has become a key requirement and national priority within the EV battery industry[104].

(1) Traditional EV batteries, particularly lithium-ion batteries (LIBs), provide the highest energy and power densities, longer lifespans, relatively low pollution, and lighter designs. However, they primarily rely on materials such as lithium, cobalt, and nickel, which have high energy consumption and environmental impacts during extraction and processing[105]. To address these challenges, green manufacturing emphasizes the use of more sustainable materials and recycling strategies. For example, studies have shown that optimizing material selection can reduce carbon emissions over the lifecycle of an EV battery by 20%. Additionally, the development of alternative chemical materials, such as lithium iron phosphate (LFP)

batteries, can reduce environmental footprints and improve recyclability[104].

Modern EV battery manufacturing incorporates advanced electrode processing technologies to improve performance and reduce waste. For example, 3D printing technologies, such as direct ink writing, enable precise material deposition, reducing waste and improving battery structure. These technologies can create complex electrode structures, enhancing charge-discharge rates and overall battery efficiency[106].

(2) As global attention to low-carbon development grows, the automotive industry, as a significant source of carbon emissions, has placed carbon footprint management at the heart of achieving sustainable development. Among the various focus areas, the carbon footprint management of NEV batteries has become a key topic. The carbon emissions associated with the battery production process account for a significant portion of the entire life cycle carbon footprint of NEVs, making the optimization of battery material selection and production processes crucial to reducing carbon footprints[107]. For instance, the European Union mandates that battery products provide carbon footprint declarations, incorporating them as an important component of the "Battery Passport", thus raising the requirements for export enterprises[56]. Additionally, China is accelerating the establishment of a carbon footprint management system for automotive products. Through the creation of a carbon footprint factor database and a carbon labeling certification system, China is promoting the low-carbon competitiveness of NEVs and power batteries.

(3) One of the most critical aspects of green manufacturing for EV batteries is recycling. Recycling plays a vital role in improving overall sustainability by reducing environmental hazards and promoting the continued use of raw materials[108]. However, the current design of battery packs is not optimized for easy disassembly. The use of adhesives, bonding methods, and fasteners makes manual or machine disassembly challenging. Traditional recycling methods are time-consuming and ineffective in meeting government standards[109]. As a result, recycling technologies such as pyrometallurgical (PR), hydrometallurgical (HR), and direct cathode recycling (DCR) are being developed to recover key metals and reduce waste[50]. For instance, DCR can recover up to 90% of critical materials, with a lower environmental impact compared to conventional methods.

Tesla's Nevada Gigafactory employs a "Wet Recycling Technology", which efficiently reprocesses materials from lithium batteries, significantly reducing CO_2 emissions. For every ton of battery material recycled, the process cuts 4.5 tons of CO_2 emissions. Additionally, Tesla's lithium recycling costs are 30% lower compared to the mining of new ores. This technology not only promotes the sustainable development of battery recycling but also greatly enhances the efficiency of material reuse.

(4) A recent study on the green manufacturing of LFP batteries demonstrated that optimizing material selection and recycling significantly reduces lifecycle carbon emissions. By using environmentally friendly materials and advanced recycling technologies, LFP batteries' carbon emissions are 25% lower than traditional LIBs. Additionally, the use of powder metallurgy and optimized processing technologies has improved material utilization by 15%-20%, further enhancing sustainability[110].

Green manufacturing technologies in EV battery production not only reduce environmental impact but also enhance efficiency and performance. By optimizing material selection, employing advanced processing technologies, and improving end-of-life management, the EV battery industry can make a significant contribution to sustainable development.

DISCUSSION

This review synthesized the application of green manufacturing processes in the precision machining of automotive components, emphasizing four core elements: material selection, energy efficiency optimization, waste minimization, and recycling/remanufacturing. By evaluating advanced technologies such as laser machining, digital twins, and micro-lubrication, the study underscores the potential of green manufacturing to reduce environmental impact while enhancing economic and operational efficiency in the automotive sector.

Collective impact of the literature

The reviewed literature collectively highlights the transformative role of green manufacturing in addressing environmental challenges. Case studies on transmission gears and engine components demonstrate tangible reductions in energy consumption (e.g., 20%-25% energy savings via high-efficiency equipment) and waste generation (e.g., 25% reduction through precision cutting). The integration of digital tools such as CAM software and IoT-enabled monitoring systems has enabled real-time optimization of processes, fostering a shift toward sustainable practices. These contributions have solidified green manufacturing as a critical pathway for achieving circular economy goals in automotive production.

Strengths of the reviewed literature

Focus on Energy Efficiency: Studies extensively explore energy-saving strategies, such as optimizing CNC machining parameters and adopting MQL technology, which reduce energy consumption by up to 37% in adaptive fluid systems [Figure 15].

Digital Innovation: The literature underscores the growing significance of advanced digital tools such as digital twins and the IoT, which are transforming industries by enabling predictive maintenance, real-time process simulation, and efficient resource optimization. For instance, the implementation of digital twins significantly enhances product lifecycle management by allowing for accurate, real-time monitoring and simulation of systems throughout their development and usage phases. This technology also reduces the likelihood of design errors by providing virtual models that mirror physical assets, ensuring that potential issues are identified and addressed before they manifest in the real world. Such innovations are a game-changer in terms of improving operational efficiency and minimizing unplanned downtimes across various industries [Figure 12].

Material Advancements: Extensive research and analysis of advanced lightweight materials, including CFRP and various aluminum alloys, reveal their substantial role in reducing vehicle weight, which can lead to weight reductions of up to 50%. These reductions contribute to improved fuel efficiency and performance, addressing the growing demand for more sustainable solutions. Additionally, these materials are integral to meeting sustainability goals, as they offer improved recyclability compared to traditional materials. This advancement is not only beneficial for automotive and aerospace industries but also plays a crucial role in reducing the overall environmental impact of manufacturing processes.

Practical Case Studies: In-depth investigations into the manufacturing processes of key automotive components, such as transmission gears and engine parts, provide valuable, actionable insights into the complexities of translating theoretical innovations into practical, industry-ready applications. These case studies serve as a bridge between theoretical concepts and their actual implementation in industrial settings, offering a comprehensive understanding of how cutting-edge technologies are applied to optimize manufacturing efficiency, reduce costs, and improve product performance.

Weaknesses and gaps in the literature

Limited Lifecycle Analysis: A significant gap in current studies is the narrow focus on the manufacturing phase, often disregarding the comprehensive analysis of the full lifecycle of products. While much attention is given to production processes, there is insufficient consideration of other critical phases such as raw material extraction, product use, and eventual disposal or recycling. This limited scope results in an incomplete understanding of the true environmental impacts of manufacturing practices. To develop more sustainable production systems, it is essential to adopt a holistic approach that evaluates the entire lifecycle of a product, including the upstream and downstream stages. By considering these stages, industries can better identify opportunities for resource optimization, waste reduction, and energy efficiency that span beyond the manufacturing floor.

Underexplored Technologies: Despite the rapidly evolving landscape of manufacturing technologies, certain emerging methods are not receiving the level of attention they deserve in the literature. For example, artificial intelligence (AI)-driven process optimization, which leverages machine learning algorithms to fine-tune manufacturing processes in real-time, holds great promise for enhancing efficiency and reducing waste. Similarly, hybrid additive-subtractive manufacturing methods - combining the benefits of AM (3D printing) with traditional subtractive techniques - could revolutionize precision engineering and material usage. Additionally, the use of bio-based lubricants, which can reduce the environmental footprint of machining processes, is another underexplored area. These technologies have the potential to significantly reduce energy consumption, material waste, and harmful emissions, yet they remain insufficiently studied in the context of green manufacturing.

Lack of Comparative Analyses: Another critical gap is the limited number of studies that conduct direct comparisons between different green technologies. For example, techniques such as MQL and dry machining offer environmentally friendly alternatives to conventional machining methods, but there is a lack of comprehensive research comparing their effectiveness in terms of cost, performance, and sustainability. Without such comparative analyses, it is challenging for industries to make informed decisions about which technologies to adopt, and whether the trade-offs between cost savings, performance improvements, and environmental benefits are worthwhile. More research is needed to evaluate the relative strengths and weaknesses of different green technologies and to guide manufacturers in choosing the most effective solutions for their specific needs.

Policy and Incentive Gaps: Finally, while technological solutions are often at the forefront of discussions on green manufacturing, there is insufficient focus on the role of policy frameworks and incentives in driving widespread adoption. Regulatory mechanisms such as carbon taxes, subsidies for green technologies, and stricter environmental standards have the potential to significantly accelerate the transition to more sustainable manufacturing practices. However, the impact of these policies on the adoption of green manufacturing solutions remains underexamined. A better understanding of how policy frameworks can facilitate the integration of green technologies is crucial to bridging the gap between technical innovation and real-world implementation. Without effective regulatory support, the adoption of green manufacturing practices may remain slow and fragmented, limiting their potential benefits.

Next steps for research

Interdisciplinary Collaboration: To overcome the technical, economic, and regulatory barriers to green manufacturing, it is crucial to foster partnerships across multiple disciplines. By encouraging collaboration between materials scientists, policymakers, and digital engineers, industries can create more comprehensive solutions that integrate scientific innovation with practical regulatory frameworks. This multidisciplinary approach will enable the development of manufacturing processes that not only optimize technical performance but also align with economic goals and regulatory requirements. The synergy between these diverse fields can lead to breakthrough technologies and policies that accelerate the transition toward sustainable manufacturing practices.

Lifecycle Integration: One of the most pressing challenges in green manufacturing is the lack of standardized metrics and frameworks to assess environmental impacts throughout the entire product lifecycle. From the early design phase to the eventual end-of-life recycling, each stage of a product's journey has environmental consequences that must be accurately measured and minimized. Developing a unified approach to lifecycle integration would enable manufacturers to evaluate the sustainability of their products in a comprehensive manner. This holistic perspective will allow for better decision-making at every stage of production, from sourcing raw materials to designing for recyclability, ensuring that sustainability is embedded in every step of the process.

Hybrid Manufacturing: The potential for hybrid manufacturing - combining AM (such as 3D printing) with traditional subtractive processes - presents an exciting opportunity to reduce material waste and energy consumption. By investigating synergies between these two manufacturing approaches, companies can minimize the material waste typically associated with subtractive methods, while also benefiting from the flexibility and precision offered by additive technologies. This fusion could lead to more sustainable manufacturing processes that utilize resources more efficiently, reducing both production costs and environmental impact. Further research into the integration of these methods will be essential for realizing their full potential.

Socio-Economic Studies: To better understand the drivers of green technology adoption, it is important to conduct socio-economic studies that analyze the influence of consumer demand, corporate incentives, and government policies. Consumer preferences for environmentally friendly products, combined with corporate incentives to reduce costs and enhance brand reputation, create a powerful market force that can drive widespread adoption of green technologies. Meanwhile, government policies, such as subsidies for clean technologies or carbon taxes, can provide additional incentives for businesses to adopt sustainable practices. Examining how these socio-economic factors interact and influence decision-making will help tailor policies and business strategies to accelerate the transition to green manufacturing.

AI and Big Data: The application of AI and big data analytics offers immense potential to optimize manufacturing processes and improve supply chain sustainability. Machine learning algorithms can be used to fine-tune real-time process parameters, predict potential equipment failures, and enhance predictive maintenance strategies. These technologies also allow for more efficient energy use and resource management, leading to reduced operational costs and a smaller environmental footprint. By leveraging AI and big data, manufacturers can make data-driven decisions that improve operational efficiency, reduce waste, and enhance the overall sustainability of the supply chain.

By addressing these research gaps, future studies can guide the automotive industry toward achieving its goal of "zero-emission" manufacturing while balancing the pressing needs of ecology, economy, and technology. Integrated strategies that combine technical innovation with regulatory support and market-driven forces will be key to achieving a sustainable manufacturing future.

CHALLENGES AND PROSPECTS

The application of green manufacturing technologies in the processing of automotive parts not only supports the sustainable development of the industry but also significantly enhances both the environmental and economic performance of enterprises. This paper provides a comprehensive overview of the achievements and challenges associated with green manufacturing processes in processing. It offers an in-depth analysis of key areas such as energy consumption control, waste management, equipment optimization, and process innovation, identifying current issues and future development opportunities. Additionally, the paper evaluates the effectiveness of green manufacturing in reducing environmental impacts and explores its potential for broader adoption within the automotive manufacturing sector, proposing a sustainable development path that balances technological innovation with ecological responsibility.

Challenges

Despite the notable successes of green manufacturing technologies, their widespread adoption and implementation continue to face significant challenges at both the technical and economic levels.

(1) High initial equipment costs present a significant barrier to the adoption of green manufacturing technologies. For instance, the cost of high-efficiency CNC machine tools, AM equipment, and environmentally friendly cooling systems is typically 30%-50% higher than that of conventional equipment[4]. Process complexity and technological barriers are also key challenges for green manufacturing. For example, while MQL technology reduces the use of cutting fluid, it imposes higher demands on equipment precision, tool life, and the optimization of process parameters[111,112].

(2) Talent shortages and insufficient technical training also pose significant challenges to green manufacturing. The complexity of green manufacturing technologies requires manufacturing enterprises to have highly skilled technical teams; however, there is a relative scarcity of trained professionals in this field[13].

(3) Uncertainty regarding long-term economic benefits is another challenge for green manufacturing. The operational and maintenance costs of AM equipment and low-energy machine tools can be high, which poses a challenge to a company's return on investment cycle[113].

(4) The promotion of green manufacturing also faces challenges in the supply chain. With the strengthening of international green trade barriers, such as the European Union's Carbon Border Adjustment Mechanism (CBAM) and battery carbon footprint regulations, the management of carbon footprints across supply chains has become particularly important[114]. However, the lack of standardized global carbon footprint accounting leads to data asymmetry and increased compliance costs.

(5) Although national and local governments have introduced a series of policies to support green manufacturing, further improvements are still needed in areas such as carbon footprint accounting standards, information disclosure, and market mechanisms[115]. For instance, China is accelerating the development of unified product carbon footprint accounting standards, such as the "Implementation Plan for Establishing a Carbon Footprint Management System" and the "Implementation Plan for Further Improving the Market-Oriented Green Technology Innovation System (2023-2025)". However, mutual recognition of standards between countries remains a challenge. At the same time, there is insufficient public awareness of green manufacturing, and consumer acceptance and demand for low-carbon products still need to be increased. Furthermore, companies may face risks such as damage to brand image and reduced market competitiveness during their green transformation process.

Future prospects

In the future, the development of green manufacturing technologies in the processing of automotive parts will increasingly integrate with smart manufacturing and digitalization. Smart manufacturing technologies, such as the Industrial IoT (IoT), AI, and digital twins, will provide robust technical support for green manufacturing[116-118]. The IoT can connect various production equipment within a factory, enabling real-time monitoring of energy efficiency and equipment health. This data helps adjust energy usage during production, ensuring that equipment operates at optimal conditions and minimizing energy waste[116]. For example, by monitoring energy consumption in real-time through an IoT system, the workload of production equipment can be adjusted, thereby reducing overall energy consumption[118]. AI can use deep learning and machine learning algorithms to monitor every stage of the production line in real time, automatically adjusting process parameters to reduce energy consumption and waste generation. Big data can assist manufacturing companies in achieving more efficient resource allocation and supply chain management. By analyzing global supply chain data, companies can select the most optimal sources of raw materials and logistics routes, thereby reducing their carbon footprint. The advancement of digital technologies will also enable more efficient resource recycling management, including material recovery tracking systems based on blockchain technology to ensure transparency and efficiency in waste recycling[119]. Ultimately, the future of green manufacturing will aim to achieve "zero emissions", including the complete elimination of chemical coolants in the production process and the use of more environmentally friendly energy sources, such as solar and wind power, to drive equipment[120,121]. The production model grounded in life cycle analysis (LCA) ensures that the processes of product production, manufacturing, use, and disposal are characterized by minimal energy consumption, reduced pollution, and enhanced recyclability. This approach aligns with the requirements for sustainable product development and utilization, optimizing the environmental impact of products throughout their life cycle, starting from the design phase[122].

The future development of green manufacturing will require multidisciplinary collaboration across fields such as materials science, computer science, mechanical engineering, and other disciplines. Advancing more environmentally friendly and high-performance alternatives to cutting fluids, developing durable and efficient cutting tool materials, and designing smarter production management systems will all necessitate a multidisciplinary approach[123,124].

Policy and regulatory directives, coupled with shifts in market demand, are accelerating the advancement of green manufacturing. An increasing number of governments and policymakers in developing countries are devising comprehensive strategies that span from manufacturing processes to the disposal of final products. A lower-impact strategy, endorsed by both developing and developed nations, aims to ensure that even the final product does not contribute to environmental pollution. To incentivize companies to adopt environmentally friendly production methods, states have implemented carbon tax policies and provided subsidies for green production[125]. Additionally, consumer preference for green products further incentivizes companies to transition to green manufacturing[126].

With the growing awareness of sustainable development and the widespread adoption of intelligent technologies, it is anticipated that green intelligent manufacturing will emerge as a promising manufacturing paradigm. This paradigm addresses the challenges associated with eco-friendly, human-centric, and economically viable development within our society[78].

DECLARATIONS

Acknowledgments

This project is grateful for the funding provided by the Henan Province Higher Education Teaching Reform Research and Practice Key Project: Exploration of Innovative Ability Training Model for Mechanical Talents in Local Universities Integrating "Specialized Innovation, Industry Education, and Science Education" (2024SJGLX0136). In addition, we extend our gratitude to Mr. Wang Hongyan, a senior postgraduate, for his invaluable assistance in data collection.

Authors' contributions

Writing - review and editing, writing - original draft: Yang, Q.
Supervision: Ming, W.

Availability of data and materials

The data that support the findings of this study are available from the Web of Science (WoS) database and the China National Knowledge Infrastructure (CNKI). Anyone can access the WoS data using the search query provided in the body of the manuscript, and the CNKI data can be accessed through the platform's search function.

Financial support and sponsorship

This project is grateful for the funding of the Henan Province Higher Education Teaching Reform Research and Practice Key Project: Exploration of Innovative Ability Training Model for Mechanical Talents in Local Universities Integrating "Specialized Innovation, Industry Education, and Science Education" (2024SJGLX0136).

Conflicts of interest

Ming, W. is an Editorial Board Member of the journal *Green Manufacturing Open*. Ming, W. was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, or decision-making. The other author declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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