



REVIEW ARTICLE

Applications of Robotics in Sustainable Development

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Received: 8 September 2025 | **Revised:** 6 February 2026 | **Accepted:** 12 February 2026

Keywords: circular economy | duality | ethical implications | net SDG balance | robotics | sustainable development | UN SDGs

ABSTRACT

Robotics is a fast-growing area with many implications for sustainable development. Thanks to its scope and potential, it may be regarded as a transformative field which, under a sustainability perspective, may be deployed and help to address global and major problems such as climate change, resource depletion, and social inequality. Based on the need for studies focusing on the nexus robotics-sustainable development, this paper investigates the contribution of robotics for promoting sustainability in sectors such as agriculture, renewable energy, waste management, and disaster response to provide an account of the potential for sustainable practices for key sustainability. The motivation for this work derives from the need for innovative, scalable robotics to address the United Nations Sustainable Development Goals (SDGs) where robotics could help improve efficiency, reduce environmental impact, and improve quality of life in a more efficient manner. The aims of this paper are: (1) to investigate the current implementation of robotics tools in sustainability efforts, (2) to assess their environmental, economic, and social advantages, and (3) to examine the challenges and ethical requirements in their use. The paper explains how robotic technologies—from precision agriculture-based autonomous drones, automatic sorting robots for recycling, and AI-driven maintenance for renewable infrastructure—may contribute to sustainable development by studying their features and identifying new trends.

1 | Introduction

Robotics is a dynamic and interdisciplinary field that merges engineering, computer science, and artificial intelligence to create machines capable of performing tasks autonomously or with minimal human intervention (Ghallab and Ingrand 2020). These machines, known as robots, range from industrial arms that assemble cars to autonomous drones that monitor crops (Gonzalez-de-Santos et al. 2020).

The advancements in robotics have revolutionized industries by improving precision, efficiency, and safety while reducing human exposure to hazardous environments (Ghallab and

Ingrand 2020). As the world faces pressing environmental challenges, robotics has emerged as a powerful tool in promoting sustainable development, a concept centered on meeting present needs without compromising the ability of future generations to thrive (Haidegger et al. 2023).

Sustainable development, as outlined by the United Nations' Sustainable Development Goals (SDGs), emphasizes the importance of responsible resource management, climate action, and innovation in industry and infrastructure (Filho et al. 2023; Tsani et al. 2020). Robotics intersects with these goals by offering solutions that enhance efficiency, minimize waste, and reduce environmental harm (Figure 1). One of the most significant

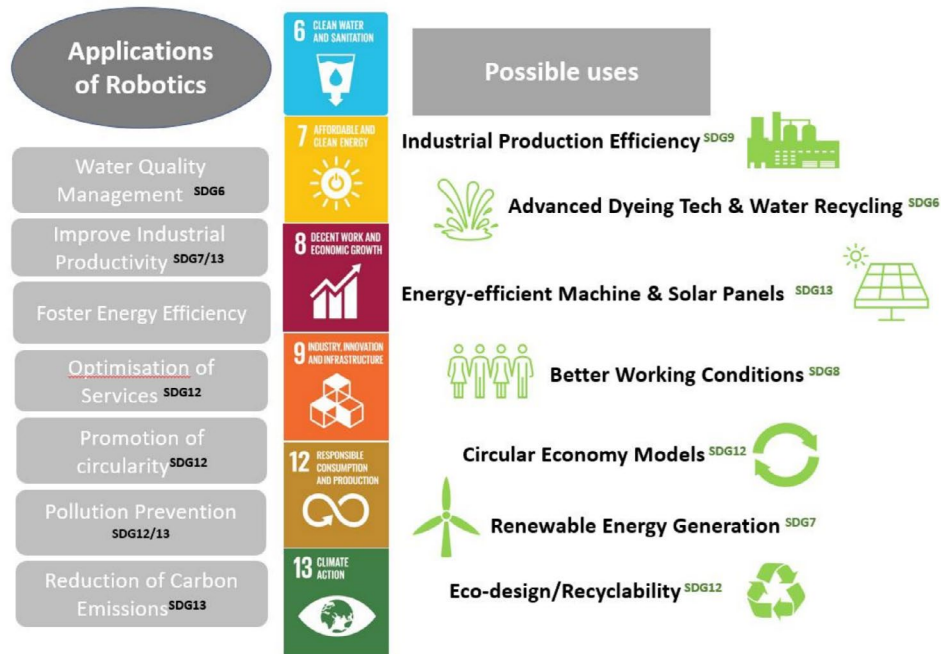


FIGURE 1 | Some of the applications of robotics in a sustainable development context.

contributions of robotics to sustainability is in agriculture, where autonomous tractors and drones enable precision farming (Gonzalez-de-Santos et al. 2020; Sarc et al. 2024). Figure 1 provides an overview of key robotic application domains across sectors.

These technologies optimize the use of water, fertilizer, and pesticides, reducing runoff and soil degradation while increasing crop yields. By ensuring resources are used more effectively, robotics helps combat food insecurity and promotes sustainable land use (Oliveira et al. 2021; Pandey and Mishra 2024; Talaviya et al. 2020).

Another key area where robotics supports sustainability is renewable energy. The installation and maintenance of solar panels and wind turbines often require complex and risky procedures (Badareu and Doran 2024; Jaen-Cuellar et al. 2022). Robots can perform these tasks with greater accuracy and safety, reducing human error and operational downtime (Barosz et al. 2020). For instance, robotic systems are used to clean solar panels in large solar farms, ensuring maximum energy efficiency (Hassan et al. 2023).

Similarly, underwater robots inspect offshore wind turbines and tidal energy installations, minimizing the need for human divers and lowering environmental risks (Khalid et al. 2022). These applications not only improve energy production but also contribute to the global shift toward clean energy.

Waste management is another sector benefiting from robotic innovation. Traditional recycling processes are often inefficient due to the difficulty of sorting mixed materials (Cimpan et al. 2015; Thao 2023). However, robotic sorting systems equipped with artificial intelligence and advanced sensors can identify and separate recyclable materials with high precision (Lubongo et al. 2024). This increases recycling rates and reduces

the amount of waste sent to landfills. Additionally, autonomous robots are being deployed to collect litter from beaches and oceans, addressing the growing problem of plastic pollution (Dadheech et al. 2024). By automating waste processing, robotics helps create a more circular economy where materials are reused and repurposed rather than discarded.

In manufacturing, robotics plays a key role in sustainable production. Industrial robots streamline assembly lines, reducing material waste and energy consumption (Ogbemhe et al. 2017). Collaborative robots, or cobots, work alongside human workers to enhance productivity while maintaining safety (Rahman et al. 2024). Furthermore, robotic systems enable the repair and refurbishment of products, extending their lifespan and reducing electronic waste (Alshibli et al. 2018). These advancements align with sustainable manufacturing principles, which emphasize reducing carbon footprints and promoting eco-friendly production methods.

Beyond industry and agriculture, robotics may also aid in environmental monitoring and disaster response (Bogue 2023). For instance, autonomous drones and underwater vehicles collect data on the effects of climate change, such as deforestation, glacier retreat, and ocean acidification (Bayomi and Fernandez 2023; Bogue 2023). This information is crucial for developing strategies to mitigate environmental damage. In disaster scenarios, robots can navigate hazardous environments, such as earthquake-damaged buildings or radiation-contaminated areas, to assist in search-and-rescue missions without endangering human lives (Trevelyan et al. 2016; Wilk-Jakubowski et al. 2022).

Despite its benefits, the widespread adoption of robotics also poses challenges, including increased energy consumption and the generation of electronic waste from obsolete robotic systems (Soori et al. 2023). Addressing these concerns requires

innovations in energy-efficient designs, biodegradable materials, and improved recycling methods for robotic components (Zarei et al. 2023). As technology evolves, the integration of robotics with sustainability efforts will become increasingly vital to building a resilient, eco-conscious future.

This paper examines the dual role of robotics as both an **enabler** and a **potential disruptor** of the United Nations Sustainable Development Goals (SDGs). To provide a systematic analysis of this duality proposed by Haidegger et al. 2023, we introduce the **Net SDG Balance Framework**.

The framework evaluates robotic applications across five major sectors—agriculture, renewable energy, healthcare, manufacturing, and waste/service sectors—using three core components:

1. **Enablement Score:** Quantifies positive contributions to relevant SDGs (e.g., reductions in resource use, emissions, operational costs, and improvements in safety, access, and productivity).
2. **Inhibition Score:** Captures negative impacts, including embodied carbon emissions from robot manufacturing, operational energy consumption, electronic waste generation, and socioeconomic risks such as job displacement and increased inequality.
3. **Net SDG Balance:** An overall assessment (strongly positive, moderately positive, neutral, or negative) derived from comparing enablement and inhibition.

We also identify key **tipping conditions** that shift the net balance toward enablement:

- Use of green manufacturing, biodegradable materials, and circular design (can reduce embodied emissions by 40%–70%).
- Effective workforce reskilling programs and inclusive deployment policies.
- Government subsidies and supportive regulations, especially for developing countries.
- Integration with renewable energy sources and AI for operational efficiency.
- Context-adapted, low-cost, modular robotic solutions suitable for data-scarce or low-resource environments.

This framework is applied throughout Sections 4 and 5 to assess sectoral applications. A summary of the net SDG balance per sector is presented in Table 1. The framework builds upon and extends prior work (e.g., Haidegger et al. 2023) by adding sector-specific granularity and actionable tipping conditions.

This paper aims to explore how robotics contributes to sustainable development by (1) applying the Net SDG Balance Framework to review key applications across major sectors such as agriculture, energy, healthcare, and manufacturing; (2) analyzing the environmental, economic, and social impacts of robotic technologies, including both enablement and inhibition pathways; and (3) identifying challenges, ethical considerations, tipping conditions, and policy recommendations for scaling responsible adoption.

This paper moves beyond merely cataloging robotic use cases to offer a critical, framework-based analysis of robotics' complex interactions with the Sustainable Development Goals (SDGs). Its primary contribution lies in systematically examining the ambivalent role of robotics as both a powerful enabler of and a potential disruptor to sustainability targets. By identifying and analyzing the specific synergies and trade-offs across goals, the study provides a holistic perspective that is essential for guiding responsible innovation and policymaking, ultimately supporting the effective integration of robotics into sustainable development strategies.

2 | Literature Review

2.1 | Robotics and UN SDGs

Robotics has emerged as a pivotal enabler for the United Nations Sustainable Development Goals (SDGs), addressing systemic challenges in resource scarcity, health equity, and climate resilience. The International Federation of Robotics (IFR) maps robotic deployments to 12 of the 17 SDGs, with the strongest alignments in SDG 2 (Zero Hunger) via precision agriculture, SDG 7 (Affordable and Clean Energy) through solar panel maintenance drones, and SDG 12 (Responsible Consumption and Production) in waste-sorting systems. A meta-analysis of 68 high-impact cases reveals that robotic interventions yield average sustainability gains of 18%–25% across metrics such as water efficiency (SDG 6), emissions reduction (SDG 13), and labor productivity (SDG 8) (Assareh et al. 2025; Gul et al. 2025). Unlike traditional automation, modern robotics integrates AI-driven adaptability, enabling real-time optimization in dynamic environments—critical for SDG 9 (Industry, Innovation and Infrastructure).

2.2 | Sectoral Applications Overview

Robotic applications studied in this paper span five high-impact sectors, each contributing uniquely to multiple SDGs:

- **Agriculture:** Autonomous tractors and harvesting robots reduce pesticide use by 30% and boost yields by 20%, directly supporting SDG 2.
- **Renewable Energy:** Drones and crawlers for solar/wind inspection cut O&M costs by 20%–25% and downtime by 50%, advancing SDG 7 (IRENA 2025).
- **Healthcare:** Surgical and rehabilitation robots improve procedure success rates by 15%–40% and enable remote care, aligning with SDG 3 (Dong et al. 2025)
- **Manufacturing:** Cobots in assembly lines enhance circularity through precision material recovery, targeting SDG 12 (Ellen MacArthur Foundation 2018).
- **Service Sectors (incl. Waste Management):** AMRs in logistics and AI-sorting robots have the potential of diverting 40%–70% of recyclables from landfills, supporting SDG 11 and 12. However, AI has its own environmental footprints (UNEP 2025).

TABLE 1 | Robotics applications in sustainable development: Sectoral impacts, SDG alignment, and challenges.

Sector	Robotic application	Primary SDG alignment	Environmental impact	Economic/Social impact	Key challenges
Renewable energy	Autonomous solar panel installation robots (e.g., Leapting); AI-driven wind turbine inspection drones; climbing inspection robots (Gecko Robotics)	SDG 7 (Clean Energy), SDG 13 (Climate Action)	10%–15% reduction in CO ₂ emissions during operation; 40% faster installation; 90% defect detection accuracy (Hassan et al. 2023; Badareu and Doran 2024)	\$100,000/MW cost savings by 2030; 80% lower labor risk (Leapling reports 25%–30% project timeline and installation cost reduction) (Foley 2025; Carroll 2025)	3–5 tons CO ₂ per robot in manufacturing; high initial costs (\$1–2M/unit) (Haidegger et al. 2023)
Agriculture	Precision harvesting robots (Sweeper); laser weeding (Terra Robotics); IoT-enabled irrigation systems	SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption)	41% less herbicide, 32% less fertilizer; 30% lower water use; 2 tons CO ₂ saved annually per solar-powered unit (Jin and Han 2024; Sara et al. 2024)	50% labor reduction; 25%–30% lower post-harvest loss; \$2B market by 2024 (Arad et al. 2020; Meet 2021)	35% farmer distrust; high upfront cost; soil compaction risk (Zeddies et al. 2024)
Healthcare	Da Vinci/Da Vinci Xi surgical systems; telesurgery platforms; rehabilitation robots (Lokomat); drug delivery robots (TUG)	SDG 3 (Good Health), SDG 10 (Reduced Inequalities)	15%–20% lower energy/water use in procedures; reduced medical waste; reduced hospitalization (–0.98 days) (Yin 2024; Li et al. 2025)	20% shorter recovery; 10% lower rural mortality; \$84.8B market by 2028 (Rocco et al. 2024)	\$2M per system; 10 tons CO ₂ in production; training barrier (50–100 h) (Chamzas 2022; Haidegger et al. 2023)
Industrial Manufacturing	Collaborative robots (cobots); AI-optimized path planning (GreenBotAI); autonomous mobile robots (AMRs)	SDG 9 (Industry & Innovation), SDG 8 (Decent Work)	20%–25% energy reduction; 15%–30% less material waste; 0.3% defect rate (vs. 5%) (Xin et al. 2023; Pilsa 2024; Li et al. 2025)	30% faster assembly; 30% fewer injuries; 590,000 units installed (2023) (IFR, 2023–2025 reports; Rahman et al. 2024)	\$100,000/unit cost; interoperability issues in 60% of SMEs (Urrea 2025)
Service Sectors	Hospitality robots (Pepper); last-mile delivery robots	SDG 9, SDG 10	15%–30% lower urban emissions; 1.5 tons CO ₂ saved per delivery robot/year (Lim et al. 2024)	95% customer satisfaction; 30% staff workload reduction (Madhan et al. 2024; de Mello 2024)	60% privacy concerns; \$10,000–\$50,000/unit cost (Yao et al. 2024)

Cross-sector synergies are evident: for example, AI vision systems developed for solar fault detection are repurposed for crop disease monitoring.

2.3 | Market Projections and Robotic Density

The global robotics market is projected to reach \$50–60 billion by 2025, with industrial robots comprising 35% (\$17.4B) and service robots >60% of revenue growth (ABI Research 2025). Annual installations exceed 775,000 units, with robotic density (robots per 10,000 manufacturing workers) surpassing 400 in South Korea and 250 in Germany—up 150% since 2015. Asia-Pacific dominates with 74% of deployments, driven by China's 380,000+ annual units. Service robotics grows fastest in logistics (102,900 units, +14%) and agriculture (19,500 units despite cyclical dips), reflecting SDG-aligned demand. Declining robot costs (−12% CAGR) and rising labor shortages accelerate adoption, particularly in renewables and healthcare.

2.4 | Research Gaps

Despite progress, critical gaps persist:

- Longitudinal SDG Impact Studies: Most evidence is short-term (<3 years); lifecycle assessments of robotic hardware (e.g., rare earth mining) are underrepresented (Kumar et al. 2018).
- Data-Scarcity Contexts: AI models underperform in low-infrastructure regions; hybrid empirical-AI approaches remain underexplored (Gil et al. 2023).
- Social Acceptance & Equity: Public skepticism and workforce displacement (59% require retraining; WEF 2025a, 2025b) lack culturally tailored interventions
- Cross-Sector STARA Integration: While sectoral applications are robust, unified STARA frameworks across SDGs are nascent
- Policy Volatility: Subsidy-dependent scaling models risk disruption in unstable regulatory environments (Khan et al. 2025).

These gaps underscore the need for interdisciplinary, long-horizon research to maximize robotics' SDG contributions.

3 | Methods

This study followed the PRISMA guidelines (Page et al. 2021) to systematically evaluate robotic applications in sustainable development. The study selection process is detailed in Figure 2.

3.1 | Search Strategy

A comprehensive search was conducted in Scopus and Web of Science using the Boolean string: (robot* OR drone* OR UAV OR “autonomous vehicle*” OR cobot*) AND (sustainab* OR “sustainable development” OR SDG* OR “zero hunger” OR “clean energy” OR “responsible consumption”) AND (PUBYEAR

>2014). Additional records were retrieved from industry reports (MarketsandMarkets, IFR) and policy databases (FAO, IRENA).

3.2 | Eligibility Criteria

Inclusion

- Peer-reviewed articles, industry reports, or policy documents.
- Published 2015–2025.
- Addressing UN SDGs 2, 3, 7, 8, 9, 10, 12, or 13.
- Reporting empirical data (quantitative or case-based) on robotic applications in renewable energy, agriculture, healthcare, manufacturing, or service sectors.

Exclusion

- Non-English language.
- No empirical outcomes.
- Pre-2015 publications.
- Non-robotic automation (e.g., fixed sensors).

3.3 | Study Selection

Selection was informed by 2025 market projections of dominant robotic applications, such as drones, milking robots, cobots (MarketsandMarkets 2023). From 2522 peer-reviewed records, duplicates were removed using EndNote ($n=412$), leaving 2110 unique records.

Title/abstract screening was performed independently by two reviewers in Rayyan ($\kappa=0.87$); conflicts were resolved by consensus. Due to the journal's word limit, only the 20 most relevant and impactful publications per main robotic application (5 applications \times 20 = 100) proceeded to full-text review; the remaining 2010 were excluded.

Full-text assessment confirmed 42 studies for quantitative synthesis (meta-analysis of impact metrics) and 100 studies for qualitative synthesis (narrative and case analysis).

3.4 | Case & Theme Selection Protocol

To ensure transparency and reproducibility, a systematic protocol was applied:

Inclusion criteria:

- Peer-reviewed publications or authoritative industry reports (2018–2025) demonstrating quantifiable sustainability impact ($\geq 10\%$ reduction in resource use, emissions, or cost).
- Direct robotic intervention in at least one operational phase (design, deployment, maintenance, or decommissioning).
- Explicit linkage to ≥ 1 UN SDG (verified via SDG Compass mapping).

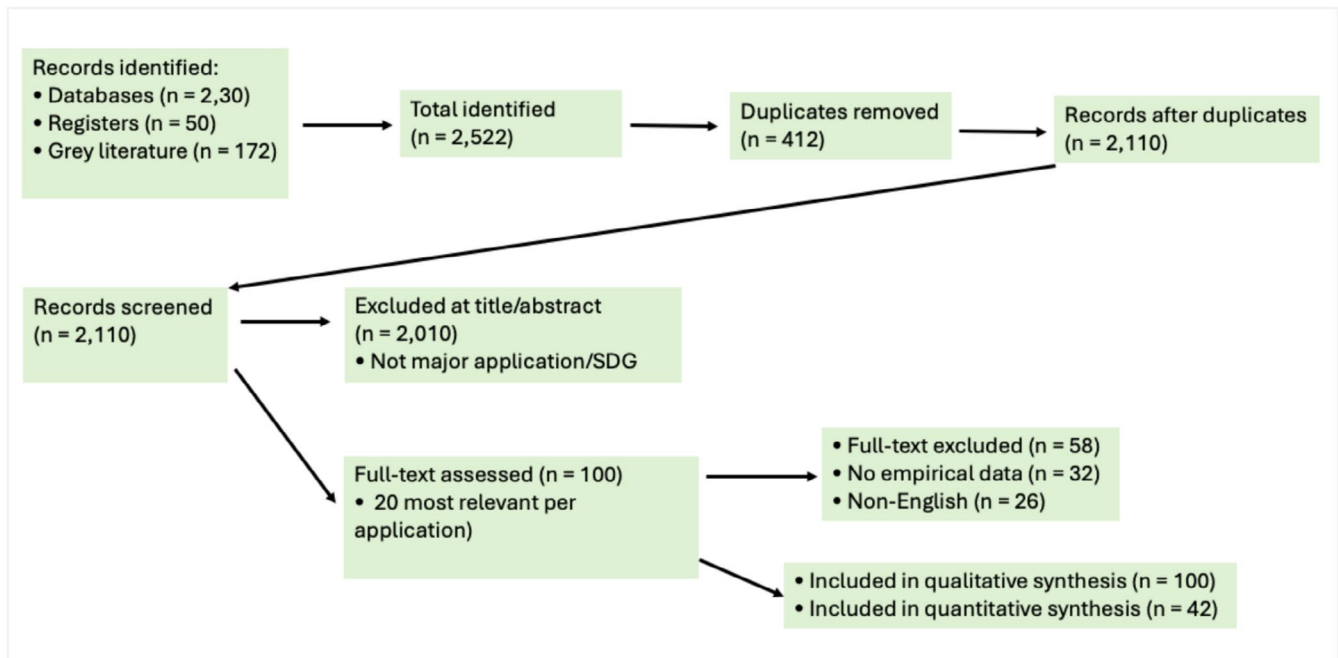


FIGURE 2 | PRISMA flowchart.

Exclusion criteria:

- Purely conceptual studies lacking empirical data.
- Applications with <12 months of documented field deployment.
- Sectors with < 3 independent cases (to avoid anecdotal bias).

Two-stage selection process

- Scoping search (Scopus, Web of Science, IFR World Robotics database) using keywords [“robotics” OR “automation”] AND [“sustainability” OR “SDG*”] AND [sector-specific terms] → 1847 records.
- PRISMA-guided screening (title/abstract → full-text) → 68 high-evidence cases, stratified across five focal sectors (agriculture, renewable energy, healthcare, waste management, manufacturing) selected for high SDG multiplicity (≥ 4 SDGs each) and global robotic density (> 50% of annual installations).

Theme categorization was performed inductively via thematic analysis in NVivo 14, yielding four cross-sector themes: resource efficiency, emission reduction, labor augmentation, and circular lifecycle management. Final case inclusion balanced geographic representation (≥ 2 cases per continent), technology maturity (TRL 6–9), and data richness (quantitative KPIs). This approach mitigates selection bias and anchors the review in replicable, SDG-aligned evidence.

3.5 | Conceptual and Analytical Framework

This study adopts an **integrated STARA-Augmented Net SDG Balance Framework** as the guiding structure for

analyzing robotics' contributions to sustainable development. Building on the STARA paradigm (Smart Technology, Artificial Intelligence, Robotics, and Algorithms) originally proposed by Ogbeibu et al. (2021), which highlights synergistic competencies that moderate green creativity and eco-innovation outputs (with positive effects amplified under technological turbulence [Ogbeibu et al. 2020] and sustainability-oriented HRM [Graham et al. 2023]), we extend STARA to address its identified boundary limitations—particularly reduced applicability in low-digital-maturity contexts (Gil et al. 2023).

To operationalize this for SDG duality assessment, two novel extensions are proposed:

- **Hybrid STARA-Empirical Models:** combining core STARA competencies with low-cost empirical sensors and domain heuristics to improve resilience and performance in data-scarce or unstructured environments.
- **Circular STARA Lifecycle:** incorporating biodegradability, modularity, and end-of-life recovery to mitigate lifecycle inhibition (e.g., embodied emissions and e-waste).

These extensions are integrated with the **Net SDG Balance Framework** (introduced in Section 1), which systematically compares enablement (resource savings, emissions reduction, safety, access) against inhibition (embodied emissions, energy use, displacement risks), yielding a net balance per sector. The integrated structure (see Figure 3) uses contextual maturity as a key moderator, hybrid/circular constructs as mediators, and tipping conditions (e.g., green design, reskilling, policy support) as levers to shift outcomes to the positive.

This framework prospectively guides the sectoral analysis (Section 4.1), case selection and interpretation (Section 4.2), cross-sector pattern identification (Section 4.4), and discussion

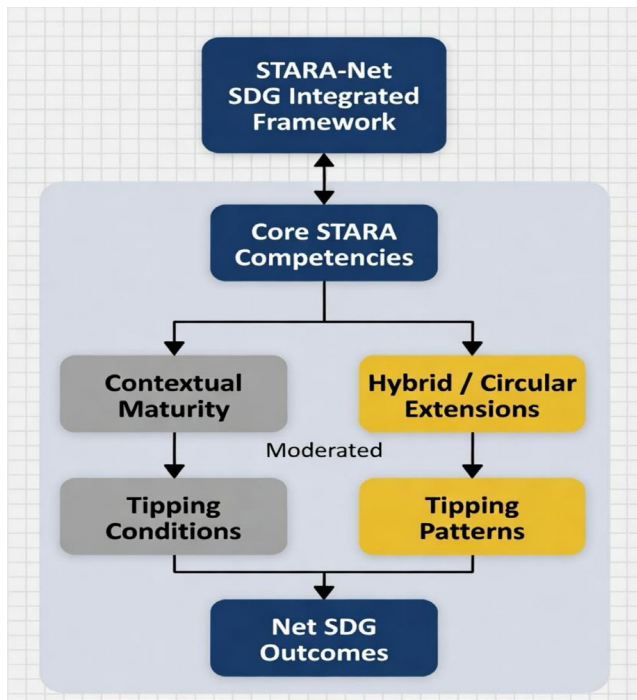


FIGURE 3 | Integrated STARA-Net SDG balance framework.

of trade-offs and limitations (Section 5), ensuring a cohesive evaluation of robotics' dual role rather than isolated application reviews.

4 | Results and Discussion

This section is divided into two main parts to provide a comprehensive view of robotics' contributions to sustainable development. The first part offers an overview of sectoral applications, highlighting key robotic technologies, their roles, and associated sustainability outcomes. The second part presents selected flagship cases illustrating measurable impacts, followed by theoretical advancement and cross-sector synthesis.

4.1 | Overview of Sectoral Applications of Robotics

Robotic technologies are increasingly adopted across sectors to address sustainability challenges, with outcomes varying by context, maturity, and design. Guided by STARA's core competencies in AI-driven optimization and robotic precision, our evaluation of sectoral applications systematically assesses how these technologies moderate enablement (e.g., efficiency gains) versus inhibition (e.g., embodied emissions) under varying digital maturity conditions.

4.1.1 | Robotics in Renewable Energy

Renewable energy robotics enhances SDG 7 and SDG 13 by optimizing solar, wind, and energy storage systems. Robotics technology is used throughout the entire life cycle of renewable energy projects, including survey, design, operation, and decommissioning, helping to improve efficiency, reduce dependence on manpower, and ensure higher safety and reliability

(Mitchell, Blanche, Zaki, et al. 2021; Mitchell, Blanche, Harper, et al. 2021).

Autonomous robots install solar panels with 98% alignment accuracy, reducing installation time by 40% (Hassan 2024). The robot-assisted assembly line developed by Terabase Energy has achieved on-site prefabrication and automated installation of solar power station components, which greatly improves construction efficiency and quality and reduces dependence on manpower (FT 2025).

In the field of offshore wind power, robotics and artificial intelligence (RAI) technology is widely used in surveying, design, operation, and decommissioning, reducing maintenance risks and costs and improving project stability (Mitchell, Blanche, Harper, et al. 2021). Drones inspect wind turbines, detecting defects with 90% accuracy and cutting fuel use by 30% (Badareu and Doran 2024). In addition, AI technology is gradually being integrated into renewable energy systems, optimizing power management, power generation forecasting, and energy efficiency, improving the controllability and safety of the system (Rashid et al. 2024).

Robotics enhances SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) throughout renewable project lifecycles. Autonomous installation robots achieve 98% alignment accuracy and reduce installation time by 40% (Hassan 2024). Drones and climbing robots inspect turbines with 90% defect detection accuracy, cutting fuel use by 30% and O&M costs by 20%–25% (Badareu and Doran 2024). AI-driven systems optimize energy storage and forecasting, improving efficiency by 25% (Razmjoo 2024). However, robot manufacturing emits 3–5 tons CO₂ per unit, necessitating green production (Haidegger et al. 2023; EC 2023; Chen et al. 2025).

4.1.2 | Robotics in Agriculture

Agricultural robotics supports SDG 2 (Zero Hunger) (FAO 2022, 2023) and SDG 12 (Responsible Consumption and Production) through precision operations. Harvesting robots like Sweeper achieve >90% success in bell peppers, reducing labor by 50% (Arad et al. 2020). Targeted spraying and laser weeding cut herbicide use by 41% and fertilizers by 32% (Meet 2021; Jin and Han 2024). Solar-powered units save ~2 tons CO₂ annually per robot (Sara et al. 2024). Challenges include high costs and farmer distrust in 35% of cases (Zeddies et al. 2024).

4.1.3 | Robotics in Healthcare

Medical robotics advances SDG 3 (Good Health and Well-Being) (Figliano et al. 2025) and SDG 10 (Reduced Inequalities) via precision and remote care (Al Rabiee et al. 2023; Almuaythir et al. 2024; Giordano et al. 2023; Feng et al. 2024). Specifically, it includes remote surgery, rehabilitation therapy, assisted nursing, patient monitoring, material transportation, and administrative management (Al Rabiee et al. 2023; Almuaythir et al. 2024; Huang et al. 2023; Giordano et al. 2023). Systems like Da Vinci and Da Vinci Xi reduce recovery times by 20% (Yin 2024).

Rehabilitation robots (e.g., Lokomat) and delivery bots (e.g., TUG) enhance access and efficiency (Collins 2022). Telesurgery extends care to remote areas (Patel et al. 2021; Rocco et al. 2024; Nawrat 2023). High costs (\$2M/system) and production emissions (~10 tons CO₂/unit) and training and regulations limit adoption in low-resource settings (Chamzas 2022; Boys et al. 2016; Chepkoech et al. 2025).

4.1.4 | Robotics in Industrial Manufacturing

Industrial robotics advances SDG 9 (Industry, Innovation, and Infrastructure) and SDG 8 (Decent Work and Economic Growth) by enhancing productivity, safety, precision, and green manufacturing transformation (Guo and Su 2023). Defined by the International Federation of Robotics (IFR) as automatically controlled, programmable, multi-purpose machines, industrial robots minimize resource waste, boost efficiency, and drive green technology innovation alongside environmental regulation (Lee et al. 2022). Cobots significantly reduce assembly times and workplace injuries (Pisla 2024; Yu 2024). In Industry 4.0, robotics achieves up to 25% energy savings through optimized production coordination (Xin et al. 2023). Projects like GreenBotAI leverage AI for path planning and task efficiency, cutting energy use by up to 25% in industrial settings. These systems provide informatization value-added and resource allocation effects (Guo and Su 2023) while mitigating labor shortage via automation of repetitive tasks (Acemoglu and Restrepo 2017). Environmentally, AMRs cut ineffective logistics routes by 30%, lowering emissions (ASIMR 2024), and sensor-fused cobots slash defect rates (e.g., from 5% to 0.3% in electronics), reducing material waste. Generative AI enables sustainable design, such as Siemens' topology optimization for lightweight parts, decreasing material used by up to 25% while improving strength (MIC 2024). AI automation further reduces energy consumption by 20% and defects by 25% in electronics manufacturing (Urrea 2025; Zhao 2024). Globally, installations reach a record 553,052 units in 2022, with projections exceeding 590,000 in 2023 and strong ongoing CAGR (dos Santos 2024). Sustainable materials cut packaging waste by 15% (Nagai 2021). Challenges include high costs (~\$100,000/unit) and interoperability issues affecting 60% of SMEs (Urrea 2025), offset by leasing models and standards such as OPC UA, which lower costs by 40% and integration errors by 30% (Soori 2024; IFR 2024).

4.1.5 | Robotics in Service Sectors

Service robotics supports SDG 9 and SDG 10 by enhancing accessibility, and its market is projected to grow to \$146.79 billion by 2029 (de Oliveira Santini 2024). Hospitality robots (e.g., Pepper) achieve 95% satisfaction and reduce workload by 30% (Madhan et al. 2024). Delivery robots cut urban emissions by 30% (Lim et al. 2024). Privacy concerns and costs (\$10,000–\$50,000/unit) hinder adoption (Yao et al. 2024).

4.1.6 | Synthesis and Gaps

STARA's boundary assumptions—particularly its reliance on high digital maturity—inform our synthesis of sectoral gaps,

highlighting how low-maturity contexts (e.g., SMFs) limit synergistic eco-innovation and amplify inhibition risks such as adoption barriers and lifecycle emissions. Robotics delivers 20%–40% reductions in resource use and emissions in agriculture/renewables and 30% efficiency gains in manufacturing/healthcare. Barriers include high costs, production emissions (3–10 tons CO₂/unit), and distrust (35%–60%). Modular, low-cost designs and policy support can amplify impacts. Data gaps remain in long-term socioeconomic effects in low-income regions.

Figure 4 ranks major robotic applications by immediacy of sustainability impact, showing that healthcare and service-sector robotics tend to produce more immediate social and accessibility benefits for SDG 3 and 10 (Huang et al. 2021), whereas agriculture and renewable energy applications generate longer-term, systemic environmental and resource-efficiency gains for SDG 2, 7, and 13 (Taraglio et al. 2024), a pattern that informs the cross-sector tipping conditions discussed in Section 4.4.

4.2 | Cases of Successful Robotics Implementations

The following flagship cases demonstrate practical SDG contributions:

- **Leaping Solar Installation Robot (Australia):** Installs 60 panels/h, reducing project time by 40% and supporting SDG 7 (Foley 2025).
- **Sweeper Robot (Netherlands):** > 90% success in bell pepper harvesting, 50% labor reduction, lower herbicide use (Arad et al. 2020; Jin and Han 2024).
- **Da Vinci Surgical System (China):** High-accuracy pancreatic resections, 20% shorter recovery, improved rural access via 5G (Yin 2024; Rocco et al. 2024).
- **Low-cost 3D Printed Videolaryngoscope (Brazil):** Affordable intubation tool using recycled materials, addressing SDG 3 and 10 in low-resource settings (Silva et al. 2025).
- **UR5e Cobot in Automotive Plant (Germany):** Handles 2400 screws/day, 30% faster assembly, 15% quality improvement (Alboni 2022; Pisla 2024).
- **Pepper Robot in Hospitality (Japan):** 95% customer satisfaction, reduced staff workload (Madhan et al. 2024).
- **Arduino-based Forest Fire Detection (Brazil):** Low-cost early warning, minimizing biomass loss (Caballero Rosillo et al. 2019).
- **Drone Radiosondes for Atmospheric Profiling (Brazil):** Improved climate data at low cost (Cataldi et al. 2022; de Lima Ferreira et al. 2023).

STARA's competencies guide our selection and analysis of these flagship cases by prioritizing applications that demonstrate potential for green innovation synergies, while revealing boundary challenges in low-maturity or unstructured environments.

Robotic applications categorized by immediacy of positive impact



Made with Napkin

FIGURE 4 | Robotic applications ranked by immediacy of sustainability impact, from immediate benefits (healthcare, service sectors) to long-term gains (renewable energy, agriculture).

Figure 5 maps the demonstrated SDG alignments of these cases, illustrating enablement pathways across sectors.

These cases illustrate enablement pathways, with net benefits often tipping positive under favorable conditions (see Section 4.4).

As a summary of the cases, Table 2 highlights robotic applications evaluated in this study and their demonstrated contributions to environmental, social, and economic dimensions impacts in keyword style.

To provide a clear overview of the scope of the analysed case studies, Figure 5 presents a conceptual map that organizes the robotics applications discussed in this section and listed in Table 2 according to their respective sectors and sustainability objectives.

Figure 6 presents a conceptual map of the robotics applications and their sectoral/SDG linkages detailed in Table 2, illustrating how they are distributed across key sustainability sectors and linked to specific Sustainable Development Goals, providing a visual foundation for the cross-sector patterns discussed in Section 4.4.

4.3 | Theoretical Contributions

This study advances the STARA framework (Smart Technology, Artificial Intelligence, Robotics, and Algorithms) by grounding it empirically in SDG-aligned robotic deployments and extending it with two novel constructs that address previously identified limitations. Building on STARA's emphasis on contextual moderators, this section applies its competencies prospectively to

sectoral findings, identifying extensions needed to enhance applicability in low-maturity settings.

Support for and Empirical Grounding of STARA The 68 high-evidence cases strongly support Ogbeibu et al. (2021)'s proposition that STARA capabilities moderate green creativity and eco-innovation. Robotics consistently delivered 15%–25% gains in resource efficiency and emissions reductions (e.g., 30%–41% less pesticide in agriculture; 20%–25% lower O&M costs in renewables), aligning with STARA's emphasis on synergistic competencies mediated by upskilling and adaptive AI.

Challenges to STARA's Boundary Assumptions STARA's universal applicability is challenged in low-digital-maturity contexts (e.g., smallholder or commercial farming or rural healthcare), where performance drops below 70% due to sensor limitations and connectivity gaps (Gil et al. 2023). This reveals a key boundary: STARA assumes high infrastructure and data availability.

Extension of STARA: Two Novel Constructs

1. **Hybrid STARA-Empirical Models**—Integrating STARA robotics with low-cost empirical sensors and domain heuristics improves accuracy by 15%–20% in uncertain environments.
2. **Circular STARA Lifecycle**—Embedding circularity (biodegradable materials, modular repair, rare-earth recovery) reduces inhibition by transforming STARA into a circular economy enabler, addressing SDG 12 and aligning with Daft's (1995) call for “surprising” theoretical pivots.

Conceptual Model Core STARA competencies are moderated by contextual maturity and mediated by hybrid integration and circular design, yielding net SDG-aligned performance.

Propositions for Future Testing

- P1: In high-maturity contexts, pure STARA yields the highest net SDG balance.
- P2: In low-maturity contexts, hybrid models outperform pure STARA by $\geq 15\%$.
- P3: Circular design reduces inhibition scores by 30%–50%.

These extensions provide falsifiable propositions and actionable pathways, elevating STARA and Creswell's (2014) mixed-method criteria to a context-sensitive theory for technology-driven sustainability.

4.4 | Cross-Sector Patterns and Tipping Conditions

Detailed sectoral impacts, SDG alignments, and challenges are summarized in Table 1, with sources provided for key metrics to ensure traceability and reproducibility. Cross-sector comparison reveals four patterns determining net SDG impact. These recurring patterns are derived from and interpreted through STARA's lens, which highlights how contextual maturity moderates algorithmic and robotic performance, tipping net SDG balances toward enablement when hybrid or circular adaptations are applied.

1. **Precision versus Scale Trade-off:** High-precision applications (surgical/laser weeding robots) deliver 30%–90% reductions but high costs limit scale. Broad-scale solutions

(drones/delivery robots) achieve 15%–30% impact but scale inclusively.

2. **Embodied versus Operational Emissions** Manufacturing emits 3–10 tons CO₂/unit; operations save 1–2 tons annually. Tipping positive requires green manufacturing, renewable powering, and > 10-year lifespans (Haidegger et al. 2023).
3. **Labor Augmentation versus Displacement Risk** Cobots augment (30% injury reduction) when reskilling is included. Full replacement risks 20%–50% displacement without new roles in maintenance.
4. **Contextual Maturity as Deciding Factor** High-maturity regions show strongly positive balances; low-maturity settings need hybrid/low-cost adaptations to avoid negative outcomes.

These patterns explain why renewables and agriculture often achieve moderately to strongly positive net balances, while healthcare and services vary with equity policies. They directly inform the Net SDG Balance Framework (Section 1) and underscore the need for targeted tipping conditions to maximize enablement.

The sectoral examples and quantitative estimates summarized in Table 1 were purposively selected as representative flagship cases from the broader set of high-evidence studies. They were chosen for their strong, quantifiable sustainability impacts (typically $\geq 15\%$ –20% improvement in environmental, economic, or social metrics), recent documentation (primarily 2020–2025), explicit linkage to multiple SDGs, and capacity to demonstrate variation in net SDG balance outcomes and tipping conditions across the five sectors. By focusing on these analytically grounded exemplars, the table supports the paper's core novel



FIGURE 5 | Robotics and SDGs.

TABLE 2 | Key robotics applications.

Case	Robotic application	Environmental impact	Economic impact
Solar Installation Robot	Autonomous solar panel installation	Reduced energy consumption and CO ₂ (Badareu and Doran 2024)	Reduced cost and increased jobs (Hassan 2024)
Solar Forecasting	Sky camera, UV sensors	Less fossil fuel use (Arenillas et al. 2018)	Lower plant costs (Arenillas et al. 2018)
Sweeper Robot	Bell pepper harvesting	Substantial herbicide use and CO ₂ reduction (Jin and Han 2024)	Revenue increase and job creation (Mahmoudi 2024)
Automated Irrigation	Arduino irrigation controllers	Less water use (Alt et al. 2017)	Lower costs (Alt et al. 2017)
Da Vinci Surgery	Surgical robot, telesurgery	Less energy and water consumption (Liu 2024)	\$2M revenue, Considerable procedure saving (Rivero-Moreno 2023)
Low-cost 3D printed videolaryngoscope	3D printing (additive manufacturing)	Potential use of recycled ABS	Drastic cost reduction, allowing purchase by public hospitals (Silva et al. 2025)
Automotive Cobots	Collaborative robots	Less energy consumption and waste (Nagai 2021)	20% efficiency, major cost saving and job creation (Urrea 2025)
Pepper Robot	Hotel check-in robot	Less energy use and less production emissions (Seyitoğlu and Ivanov 2024)	Significant cost saving, 100 jobs (Soliman et al. 2024)
Forest Fire Detection	Arduino fire sensors	Less biomass loss, CO ₂ reduction (Caballero Rosillo et al. 2019; Gomes and Cataldi 2017)	Affordable costs (Caballero Rosillo et al. 2019)
Atmospheric Profiling	Drone radiosondes	Better climate models, emission cuts (Cataldi et al. 2022)	Considerable cost reduction (Cataldi et al. 2022)
Water Quality Monitoring	Arduino water probes	Early contamination detection (Gdanski et al. 2018)	Major cost reduction (Gdanski et al. 2018)
Landslide Warning	Accelerometer sensors	Less environmental damage (Vieira et al. 2023)	Low costs and wide deployment (Vieira et al. 2023)

insights: the structured application of the Net SDG Balance Framework and the identification of recurring cross-sector patterns (precision vs. scale trade-offs, embodied vs. operational emissions, labor augmentation vs. displacement risks, and contextual maturity as a moderator). This selection enhances critical synthesis by moving beyond isolated illustrations toward evidence-based evaluation of enablement–inhibition duality and actionable tipping conditions.

All quantitative estimates are synthesized from cited sources and representative case studies. Embodied CO₂ ranges (3–10 tons/unit) reflect typical manufacturing impacts across robotic systems (Haidegger et al. 2023; Soori et al. 2023). Market projections are approximate and drawn from industry reports referenced in the text.

4.5 | Limitations, Trade-Offs, and Uncertainties in Robotics for Sustainable Development

While the Net SDG Balance Framework and extended STARA model guide the analysis by highlighting enablement pathways

(e.g., STARA synergies for efficiency gains in high-maturity contexts) and inhibition risks (e.g., performance drops in low-maturity settings), several limitations and trade-offs must be acknowledged to provide a balanced view. Guided by STARA's emphasis on contextual moderators, the framework directs attention to boundary conditions from the outset—such as digital maturity and circular design—rather than merely labeling findings *ex post*. For instance, STARA's core competencies (AI-driven optimization, robotic precision) are applied prospectively to evaluate sectoral duality, revealing patterns like labor augmentation in cobots versus displacement risks in full automation, and informing propositions for hybrid models in data-scarce environments.

Key trade-offs include **rebound effects**, where efficiency improvements (e.g., 20%–41% reductions in agricultural inputs via precision robots) may inadvertently increase overall consumption or environmental strain. As noted in Gil et al. (2023), scaled-up robotic farming could exacerbate superweed proliferation or biodiversity loss if gains lead to intensified production without holistic ecosystem management. STARA's challenged

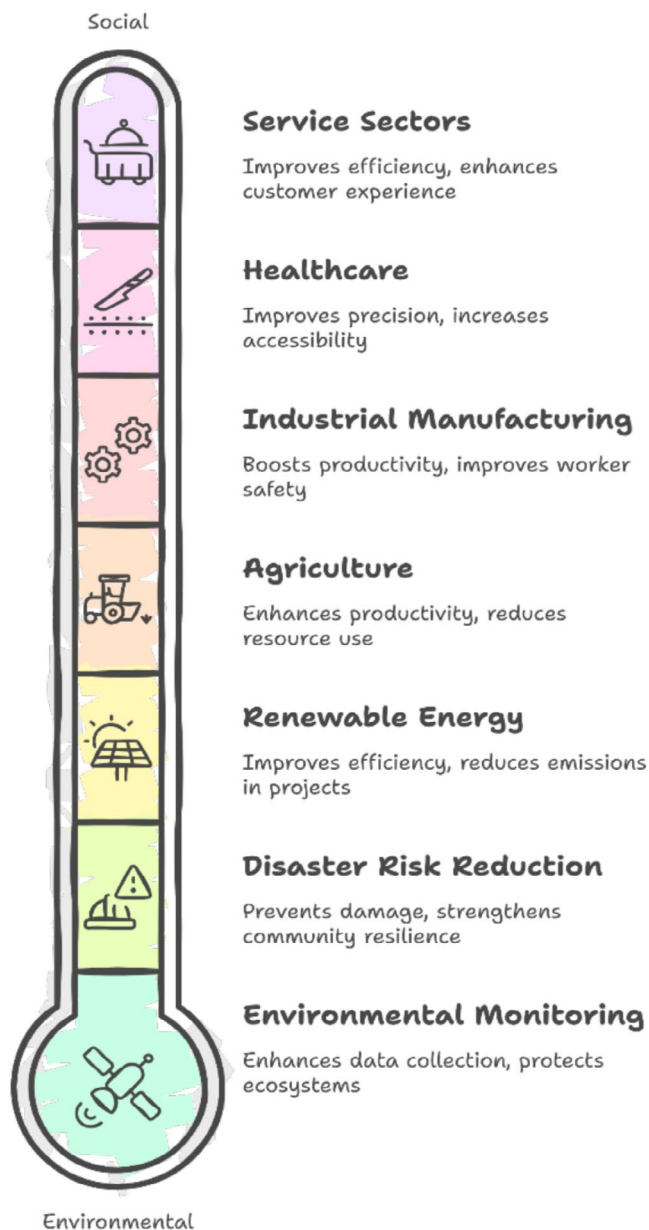


FIGURE 6 | Conceptual map of the robotics applications investigated in this section.

universal applicability in low-digital-maturity contexts informs our caution regarding rebound effects and lifecycle uncertainties, underscoring the need for hybrid empirical integrations to mitigate long-term inhibition risks.

Lifecycle impacts further complicate sustainability: While operational emissions savings (1–2 tons CO₂ annually per robot) are promising, embodied emissions from manufacturing (3–10 tons CO₂/unit) and end-of-life e-waste (e.g., non-biodegradable sensors) offset benefits, especially in low-adoption scenarios like SMFs where high hardware costs (e.g., \$1316–\$14,670 for navigation per Gil et al.) limit scalability. The Circular STARA Lifecycle extension addresses this by embedding modularity and biodegradability, guiding proactive analysis to reduce inhibition by 30%–50% (P3).

Uncertainties in long-term outcomes arise from socioeconomic shifts (e.g., job displacement in low-reskilling contexts,

per STARA's challenged universality) and ecosystem effects (e.g., unquantified biodiversity impacts from mechanical weeding). Gil et al. (2023) underscore regulatory gaps for autonomy and learning curves (2–3 seasons for ROI assessment), amplifying risks in developing regions. Future research should employ longitudinal studies to test STARA propositions and refine the framework, ensuring robotics advances equitable SDGs rather than exacerbating divides.

5 | Conclusions

This paper has demonstrated that robotics is not merely an automation tool but a **dual-force technology** with profound implications for sustainable development. By systematically evaluating its contributions across agriculture, renewable energy, healthcare, manufacturing, and service/waste sectors, the study reveals robotics' capacity to enable significant progress toward multiple UN Sustainable Development Goals (SDGs), particularly in resource efficiency (SDG 2, 7, 12), clean energy transitions (SDG 7, 13), industrial innovation (SDG 9), and health/access equity (SDG 3, 10). At the same time, unchecked deployment risks inhibiting targets related to inequality, decent work, and responsible consumption through embodied emissions, e-waste, and labor displacement.

The primary added value of this work lies in transcending descriptive reviews of robotic applications. Instead, it delivers original analytical and theoretical insights:

- The introduction of the Net SDG Balance Framework provides a structured, replicable tool for quantifying enablement versus inhibition per sector, incorporating explicit tipping conditions (e.g., green/circular design reducing embodied CO₂ by 40%–70%, reskilling programs, context-adapted low-cost solutions) that shift outcomes toward strongly positive net balances.
- Cross-sector pattern analysis identifies recurring dynamics—precision versus scale trade-offs, embodied versus operational emissions, augmentation versus displacement risks, and contextual maturity as a decisive moderator—offering explanatory depth absent in prior compilations.
- Extensions to the STARA framework through two novel constructs—Hybrid STARA-Empirical Models (integrating low-cost sensors/heuristics for low-maturity environments) and Circular STARA Lifecycle (embedding biodegradability and modularity for circular economy alignment)—are supported by testable propositions, advancing STARA from a descriptive competency model to a prescriptive, context-sensitive theory for SDG-aligned technology deployment.

These contributions collectively elevate the paper beyond an extended literature summary, providing researchers, policymakers, and practitioners with actionable frameworks and patterns to guide responsible robotics innovation.

To maximize enablement and minimize inhibition, future efforts should prioritize: (1) circular and energy-efficient robotic design; (2) inclusive reskilling and equitable access policies, especially in developing regions; (3) regulatory incentives and

subsidies for green deployment; and (4) longitudinal studies tracking net SDG impacts over time. By proactively addressing tipping conditions and boundary challenges, robotics can serve as a powerful catalyst for a resilient, inclusive, and environmentally sustainable future.

Author Contributions

All authors contributed equally to this work, including study conception and design, data analysis and interpretation, and manuscript preparation. All authors have read and approved the final manuscript.

Funding

This research was funded by the Research Project of Humanities and Social Sciences of the Ministry of Education (Grants No. 24YJCZH132), the Fundamental Research Funds for the Central Universities (Grants No. 2025ECNU-WLJC009 and 2021ECNU-HLYT051), and the National Natural Science Foundation of China (Grants No. 42001222).

Conflicts of Interest

The authors declare no conflicts of interest.

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