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Research Article

ERP-Powered ESG Intelligence: Measuring Carbon Footprint of Medical Device Supply Chains

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Abstract:

There is a growing demand for environmental sustainability in the medical device industry. Globally, the healthcare systems' carbon emissions are largely attributable to complex supply chains, including raw materials extraction, product manufacture, distribution, and disposal. Today, ERP has evolved into sustainability intelligence software for monitoring and measuring environmental performance, enabling real-time carbon footprint tracking in procurement, manufacturing, and distribution. Modern ERP may deliver ESG modules for Scope 1, 2, and 3 emissions management, and help organizations meet quality management system regulations of medical device manufacturing. Artificial intelligence algorithms can increase the accuracy of emission factors and promote carbon accounting through the automatic classification of procurement data, classification of supplier features, and natural language processing of environmental documentation. Regulatory frameworks such as the EU Corporate Sustainability Reporting Directive (CSRD) and voluntary frameworks such as CDP climate disclosure are pressuring medtech companies to develop carbon accounting capability. ERP-enabled dashboards provide product-level carbon footprints, supplier engagement platforms, and hotspots for focused decarbonization activities while automating carbon accounting and reporting in compliance with global standards. Medical device companies adopting integrated ESG intelligence systems have a competitive advantage in regulatory compliance, operational efficiency, sustainability-linked funding, and distinguishing themselves in the sustainable healthcare market. By extending from retrospective environmental reporting to predictive carbon management, medical technology companies are positioned to lead healthcare, accelerate change, and meet growing stakeholder demand for climate transparency and assurance across global value chains.

1. Introduction

The health care sector has been identified as an area for intervention globally in relation to climate and sustainability, due to the international supply chain for parts and high energy use, contributing considerably to global carbon emissions. Health care sector climate emissions are a meaningful part of overall global emissions, driven by the medical supply chain, energy use in buildings, and transportation [1]. The medical technology ecosystem presents companies with unique challenges for measuring and managing their climate footprint. The manufacturing process must comply with strict product safety and quality assurance standards that require constant measurement and monitoring of all environmental conditions. Global supply chains, which are made up of hundreds of suppliers, can add to this complexity. The climate responsibility of providing healthcare to patients requires the development of carbon accounting capabilities that do not compromise either the integrity of the product or patient safety.Enterprise Resource Planning (ERP) systems are evolving from business management systems to sustainability intelligence systems, allowing the inclusion of environmental information into the operational process. Some newer ERP systems include as modules ESG data gathering, emissions calculations, and reporting against national and international ESG regulations and standards [2]. These applications integrate with goods procurement, manufacturing execution systems, energy management systems, and logistics

tracking systems, resulting in audited carbon footprints useful for decarbonization. In the US, the FDA and multiple ISO certifications with more stringent environmental requirements from investors, customers, and government agencies drive sustainability dashboards in ERP systems. They are used to assist the medical device manufacturing industry in adhering to quality management systems regulations and environmental, social, and governance (ESG) sustainability disclosures. This technological capability, combined with increased regulatory scrutiny, provides the inflection point where environmental performance measurement goes from being an ancillary corporate social responsibility program to being a necessary business infrastructure prerequisite for market access and competitive advantage.

2. ERP Integration Architecture for ESG Data Capture

Architectural requirements for ERP-enabled ESG intelligence systems are system integrations across heterogeneous domains where sustainability management has often operated in silos. Medical device manufacturers typically deploy ERP systems connecting procurement databases, manufacturing execution systems, quality management systems, warehouses, and transportation logistics into integrated data ecosystems where each transaction is tied to specific environmental metrics [2]. More specifically, integration architecture allows carbon footprints to be automatically calculated at a transactional level. So, carbon emissions from each purchase order, production run, sterilization cycle, and shipment of product become part of a company's carbon footprint without manual data entry or estimation. Technically, this involves middleware layers that convert operational data into standardized emission factors, apply relevant calculation methodologies based on the type of activity and its geographic location, and aggregate results across corporate hierarchies from production lines upwards through company sites up to the global level.Data from other sources may be collected, such as from Internet of Things (IoT) sensors, smart meters, and real-time monitoring systems throughout the factory and logistics network. In medical device facilities, energy consumption is a key consideration, where clean room areas, sterilizers, and cold chain storage have very different energy consumption patterns than conventional manufacturing. [3] Advanced metering infrastructure captures electricity, natural gas, steam, and compressed air consumption at the equipment level and is used to assign energy costs and associated greenhouse gas emissions to product families or manufacturing processes. This data enables energy optimization efforts that can identify equipment that is not performing as expected, determine whether specific energy-intensive processes can be optimally scheduled during times of low grid carbon intensity, and estimate greenhouse gas emissions reductions for numerous facility upgrade or renewable energy procurement projects.Real-time data from IoT systems feeding into ERP systems can be used to create dynamic carbon accounting based on actual production conditions rather than annual or industry average benchmarks [3]. Operational telemetry, for example, from temperature and humidity sensors in cleanrooms, flow meters on sterilization autoclaves, or refrigeration compliance in cold storage facilities, is directly related to energy consumption. Using machine learning algorithms, these telemetry streams can be analyzed to baseline normal operational performance, note the presence of anomalies (such as equipment failure or process inefficiencies), and predict future energy consumption based upon operational production forecasts. Digital twins of plant operations can be created using operational technology and information technology to model, optimally manage, and continuously improve environmental performance through feedback from real-time measurements and predictive algorithms.Master data management capabilities within modern ERP architectures store global emission factors, carbon intensities of materials, logistics emission rates, and regulatory conversion standards in centralized repositories to ensure global consistency [4]. These repositories obtain authoritative data from government environmental agencies, international standard organizations, and industry-specific life cycle assessment databases as these authorities release new emission factors and regulatory guidance. The master data structure supports multi-dimensional emission factor selection, e.g., defining different emission factors for each material category, supplier location, manufacturing technology, transportation mode, and seasonal variation in grid carbon intensity. This enables medical device manufacturers to move from a generic industry average-based carbon accounting approach to supplier, process, and product-specific carbon accounting based on the actual environmental performance of their particular product supply chain configurations.

3. Comprehensive Carbon Footprint Calculation Methodologies

Carbon footprinting of medical devices must consider emissions across the entire product life cycle, including the extraction of raw materials, manufacturing, distribution, clinical use, and end-of-life disposal as per globally recognized standards. The healthcare sector makes a substantial contribution to the worldwide total of greenhouse gas emissions due to complicated supply chains, energy-intensive manufacturing, distribution on a global scale, and specialist disposal of medical products [1]. Medical device Scope 1 emissions include stationary combustion emissions from natural gas-fired boilers and emergency generator sets, and process emissions from ethylene oxide gas sterilization or other chemical processes. Manufacturing Scope 1 emissions are direct emissions within the organizational boundary that the medical device manufacturer has operational control over. Scope 1 emissions are relatively easy to quantify, as they can be estimated from fuel purchase invoices, hours of equipment operation, and process engineering correlations.For many medical devices, substantial Scope 2 emissions from purchased electricity and thermal energy are due to the specialized treatment requirements of manufacturing areas in regulated manufacturing facilities [3]. Cleanroom areas are required in regulated manufacturing to control particulate, temperature, and humidity. They can consume an order of magnitude more energy than other areas of the facility. Air handling systems are continually operational and not part of the production schedule. The high energy requirements of sterilizing equipment such as steam autoclaves, dry heat ovens, and radiation equipment, as well as cold chain storage for temperature-sensitive components and finished products, may pose environmental hazards due to refrigerant leaks. ERP systems integrating building management systems can then calculate energy consumption at the facility, department, and equipment level, applying location-based emission factors that take into account local electrical grid carbon intensity or market-based emission factors appropriate for organizations that buy renewable energy certificates or enter into a power purchase agreement.For medical devices, scope 3 emissions are generally the most difficult to assess, and they also make up the largest share of total emissions for the sector [5]. The upstream scope 3 categories include purchased goods and services with a high carbon footprint, such as metal alloys in implantable devices, specialized polymers that use petroleum feedstocks, and electronic devices with complex semiconductor fabrication. Transportation & distribution emissions are incurred for incoming logistics for the transport of components and raw materials, including by ocean freight, by air freight, and via temperature-controlled vehicles for the cold chain. CAPITAL GOODS emissions are incurred during plant construction, the purchase of machinery and equipment, and the construction of upstream and downstream infrastructure. Scope 3 emissions from the life phase include single-use devices going through medical waste streams requiring incineration at a specialized medical waste incineration plant, and for powered devices during the clinical use phase.At a product level, carbon footprinting enables medical device manufacturers to allocate each product SKU's share of facility-level emissions, shared equipment utilization, and overhead activities to enable eco-design of products, eco-labeling programs, and customer requests for environmental product declarations (EPD) [5]. This involves making allocations based on production volumes, the level of complexity of the manufacturing processes, or using activity-based costing approaches. Cradle-to-grave carbon accounting is based on life cycle assessment and includes carbon emissions for extraction, refining, supplier component manufacturing and assembly, packaging manufacture, distribution, and clinical use scenarios. Product carbon footprints can feed back into product design for lower carbon in materials and packaging, manufacturing process for efficiency improvements, and distribution for regional strategies or mode shifts from air and freight to ocean when clinically allowable.

4. AI-Enhanced Emission Factor Mapping and Supplier Collaboration

Accurate carbon accounting, particularly for scope 3 emissions, relies on the availability of emission factors that are customized to reflect the carbon intensity of materials, processes, suppliers, and logistics operations used in a particular company or project, rather than sector averages that can obscure important variation across the supply chain. Artificial intelligence and machine learning algorithms can improve the accuracy of emission factors for carbon accounting by recognizing patterns in procurement data, supplier characteristics, geographic conditions, and process parameters, then recommending the most relevant factors from large databases [8]. Natural language processing extracts quantitative data on carbon intensity, energy, and waste from unstructured supplier documents (sustainability reports, environmental product declarations, corporate sustainability reporting). Emission values are validated against industry standards, statistical

distributions, and peer companies, and captured in ERP master data feeds, which have confidence scores based on data source quality and emission factor data timeliness.

Machine learning models are trained on prior supply chain emissions and purchasing data, enabling them to identify relationships between supplier characteristics and real carbon performance and predict emissions of unreported primary environmental data [8]. These algorithms group suppliers into a variety of carbon intensity categories based on geographical region, industry sector, facility certifications, renewable energy objectives, and process technologies, and compatible emission factors are applied to each category. These capabilities are particularly useful for Scope 3 accounting of medical device supply chains with thousands of suppliers, for which it is infeasible to collect supplier-level primary data for all suppliers. Accuracy improves over time with active learning as more supplier data becomes available. In addition, suppliers with reported emissions far exceeding model-predicted values may be flagged for targeted verification or engagement with suppliers to reduce emissions.Supplier engagement platforms with manufacturer ERP systems ease common environmental data exchange, including secure portals, automated questionnaires utilizing CDP, EcoVadis, and other assessment methodologies, and API connections for carbon data exchange between systems [8]. Today, most of the largest medical device manufacturers are integrating environmental performance criteria into their supplier qualification process, requesting carbon intensity declarations alongside technical and pricing proposals, and establishing supplier contracts with annual emission reporting obligations for calculated suppliers. Blockchain technology can be used to record supplier-reported emission data on immutable ledgers and produce verifiable chains of custody for external assurance and fraud-proofing of previous data. Smart contracts can also be employed to implement sustainability-linked payments that reward verified emission reductions or penalize suppliers who fail to make environmental improvements.The EU Corporate Sustainability Reporting Directive is forcing medical device manufacturers to collect high-quality environmental data on suppliers across their entire service and product value chain. It is also driving supplier engagement programs, including: providing carbon accounting training; emission factor databases; and technical support for the development of supplier-specific carbon footprints. Collaborating on decarbonization may result in GHG reduction targets, cost-sharing for renewable energy investments, improved efficiency in the utilization of equipment, and preferred supplier status for low-carbon-footprint suppliers. Calculated collaboration enables greater supplier transparency through cascading visibility further up into the supply chain, as first-tier suppliers encourage their upstream suppliers to adopt similar practices and thus broaden the traceability of opaque portions of the value chain. Carbon performance, cost, quality, and delivery can be optimized to help make better sourcing decisions.

5. Regulatory Compliance, Reporting Frameworks, and Strategic Applications

For medical device manufacturers, sustainability regulations add additional complexity to the existing legal and regulatory product safety, quality management, and clinical performance requirements. An important piece of sustainability regulation is the EU Corporate Sustainability Reporting Directive (CSRD), which creates new disclosure obligations on large firms and SMEs listed on EU-regulated markets across all economic sectors, including the medical technology sector [9]. Double materiality assessment principles require organizations to measure and disclose their negative environmental impacts on nature and communities, as well as the extent to which climate-related risks affect financial performance, asset values, and business continuity. Medical device companies must report scope 1, 2, and 3 GHG emissions data, energy consumption disaggregated by renewable and non-renewable sources, water consumption and discharge volume, waste generated and diversion, and biodiversity impacts related to facilities, including those associated with the companies' supply chain.CSRD requires annual reporting not only at the entity level, but across the entirety of its value chain of impacts. This includes data-intensive efforts to collect supplier data and apply complex Scope 3 accounting methodologies [9], which include emissions from purchased goods and services, capital goods, upstream and downstream transportation and distribution, processing and using of sold products, and end-of-life treatment of sold products. Member states shall provide for exemptions from the obligation to make disclosures if compliance is not possible, despite the undertaking of reasonable efforts. Otherwise, the directive makes clear that the assurance requirement applies, and that sustainability disclosures shall be gradually subject to reasonable assurance, including at the same scope as financial statement audits. These requirements can be met by

ERP-based ESG systems as data is automatically aggregated from operating systems, calculations are built-in and mapped to regulations, detailed audit trails of data sources and transformations are in place, and regulatory-compliant reports (including machine-readable XBRL taxonomies) are generated.CDP climate change questionnaires are voluntary disclosure frameworks, effectively mandatory as institutional investors, business buyers, and members of the supply chain require CDP participation as a proof point of climate management maturity [10]. The questionnaires address: governance arrangements, business strategy alignment with climate scenarios, climate-related risks and opportunities, a company-wide greenhouse gas emissions inventory (Scopes 1, 2, and 3), greenhouse gas emissions targets, progress against targets, and climate-related financial impacts. The CDP scoring scheme rewards supply chain visibility, science-based targets, renewable energy, and demonstrated emissions reductions, and uses that information to inform both investment decisions and sustainability indices. Medical device manufacturers leverage their ERPs to populate CDP requests, allowing their systems to calculate data and frame the narrative on environmental strategy, risks, and performance trends.In practice, ERP-driven ESG intelligence drives not only compliance reporting but also procurement, product development, manufacturing, and customer interaction [10]. Carbon-weighted supplier scorecards that comprise environmental KPIs along with price, quality, delivery, and financial risk indicators enable procurement functions to analyze sourcing strategies that lower the total cost of ownership of goods, including carbon pricing scenarios. Product development teams use SKU-level carbon footprints to set product emissions reduction targets, assess the opportunities for material substitution and packaging specifications redesign, and secure eco-label certifications to differentiate their products in greener markets. Sustainability-linked financing instruments include green bonds and Environmental, Social, and Governance (ESG) linked revolving credit facilities, which offer favorable financing terms to issuers that reach ESG performance targets, as verified by a third party. ERP systems provide measurement infrastructure for covenant compliance monitoring.

6. Gap and Industry Contribution Current Industry Limitations

The medical device manufacturing sector currently operates with fragmented and inadequate carbon accounting systems that fail to meet the evolving demands of regulatory bodies, healthcare customers, and sustainability-conscious investors. Most organizations rely on disconnected spreadsheet-based tracking methods, manual data compilation from suppliers, and annual retrospective carbon inventories that provide limited actionable intelligence for operational decision-making. Existing sustainability management platforms operate in isolation from core Enterprise Resource Planning systems, creating data silos where procurement transactions, manufacturing operations, and logistics activities remain disconnected from their associated environmental impacts. The industry lacks standardized methodologies for product-level carbon footprinting specific to medical devices, where stringent quality management requirements, specialized sterilization processes, and complex multi-tier supply chains create unique measurement challenges not addressed by generic carbon accounting frameworks designed for conventional manufacturing sectors.Furthermore, medical device manufacturers struggle with Scope 3 emissions quantification across global supply networks involving thousands of component suppliers, contract manufacturers, and distribution partners who themselves lack sophisticated carbon tracking capabilities. The absence of supplier-specific emission factors forces organizations to rely on broad industry averages that obscure significant performance variations between suppliers and prevent informed sourcing decisions, balancing cost, quality, and environmental criteria. Current artificial intelligence applications in sustainability remain nascent within the medical technology sector, with limited deployment of machine learning algorithms for emission factor classification, natural language processing for supplier data extraction, or predictive modeling to fill carbon data gaps. The disconnect between environmental reporting systems and quality management infrastructure required under FDA regulations and ISO certifications creates compliance burdens where separate documentation streams must satisfy both product safety authorities and sustainability disclosure frameworks without leveraging synergies between these governance systems.

7. How this Article Advances Industry Practice

This article provides medical device manufacturers with a comprehensive implementation framework for ERP-powered ESG intelligence systems that integrate carbon accounting directly into operational workflows, transforming sustainability

from a peripheral reporting function into embedded business infrastructure. The content addresses the critical gap between generic ERP sustainability modules and the specialized requirements of medical device supply chains by detailing how to configure carbon calculation engines for sterilization energy consumption, cleanroom operations, temperature-controlled logistics, and medical waste disposal pathways specific to healthcare products. By synthesizing regulatory requirements from the EU Corporate Sustainability Reporting Directive, CDP climate disclosure frameworks, and medical device quality standards, the article establishes a unified compliance architecture enabling organizations to simultaneously satisfy environmental reporting mandates and product safety documentation obligations through shared data infrastructure and audit trail capabilities.The article advances industry practice by providing actionable guidance on artificial intelligence deployment for emission factor mapping, supplier carbon data extraction, and predictive modeling that addresses the pervasive challenge of incomplete Scope 3 data across multi-tier medical device supply networks. Organizations implementing the AI-enhanced supplier collaboration frameworks detailed here can systematically engage thousands of suppliers, automate carbon data collection through secure portals and API integrations, and apply machine learning algorithms to predict emissions for suppliers not yet providing primary environmental data. The strategic applications section demonstrates how leading medical technology firms leverage ERP-generated carbon intelligence beyond compliance reporting to inform carbon-weighted procurement decisions, optimize product portfolios toward lower-emission device designs, access sustainability-linked financing instruments with favorable terms, and differentiate offerings in healthcare markets where hospital systems increasingly evaluate supplier environmental performance as part of their own Scope 3 reduction strategies.This article equips sustainability leaders, operations managers, IT architects, and executive decision-makers with the technical specifications, implementation roadmaps, and business case justifications necessary to champion ERP-ESG integration projects within their organizations, accelerating industry-wide transformation toward transparent, verifiable, and strategically valuable carbon accounting capabilities that position medical device manufacturers for competitive advantage in an increasingly environmentally regulated and sustainability-conscious healthcare marketplace.

Table 1: *ERP Integration Architecture Components for ESG Data Capture [3, 4]*

Integration Layer	Data Sources	ESG Metrics Captured	Technology Enablers
Transactional Data Collection	Procurement systems, production orders, logistics records	Material quantities, energy consumption, transportation distances	APIs, middleware platforms
Real-Time Monitoring	IoT sensors, smart meters, building management systems	Equipment-level energy usage, cleanroom environmental conditions	IoT devices, edge computing
Supplier Data Exchange	Supplier portals, collaboration platforms, and EDI systems	Supplier-specific emission factors, carbon intensity values	Blockchain verification, secure APIs
Master Data Management	Emission factor databases, regulatory standards, and material libraries	Carbon intensities, conversion factors, and regional grid emissions	Centralized repositories, automated updates

Table 2: *Carbon Footprint Calculation Scope Categories for Medical Devices [5, 6]*

Emission Scope	Boundary Definition	Medical Device Examples	Calculation Methodology
Scope 1 (Direct)	Owned or controlled sources	Natural gas boilers, ethylene oxide sterilization, and company vehicles	Fuel purchase records, equipment runtime monitoring
Scope 2 (Indirect Energy)	Purchased electricity and thermal energy	Cleanroom HVAC systems, autoclave sterilization, cold chain storage	Utility bills, location-based or market-based emission factors
Scope 3 (Value Chain Upstream)	Purchased goods, capital equipment, and inbound transportation	Raw material extraction, component manufacturing, supplier logistics	Spend-based analysis, supplier-specific data, LCA databases
Scope 3 (Value Chain Downstream)	Distribution, product use, and end-of-life disposal	Temperature-controlled transport, powered device operation, and medical waste incineration	Activity-based calculation, use-phase modeling, waste disposal records

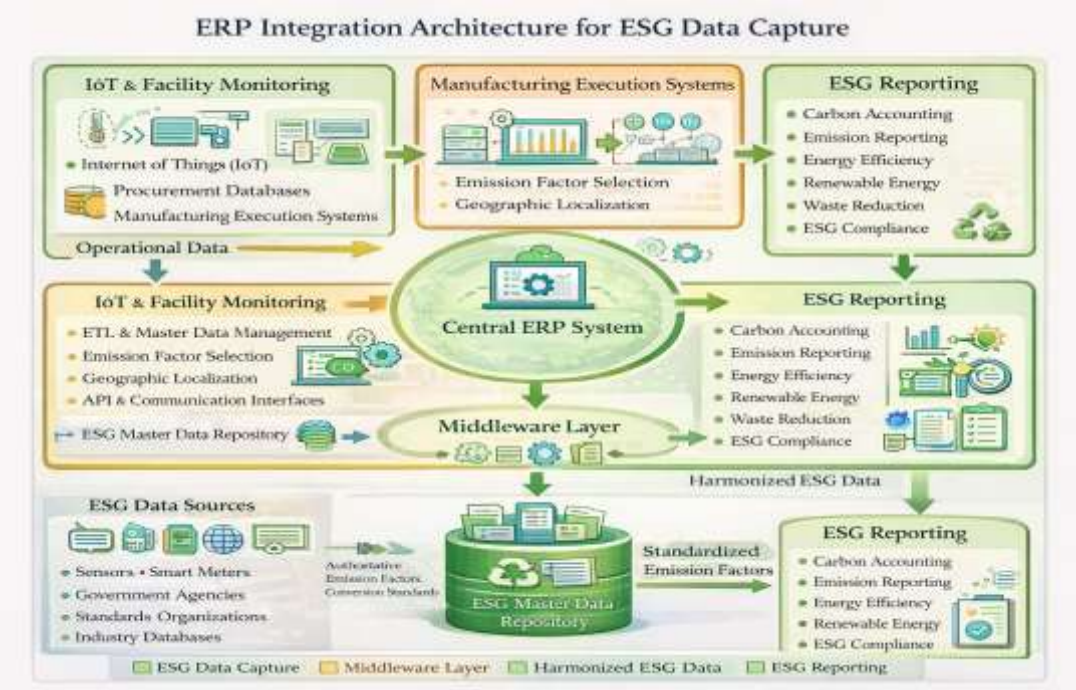

***Figure 1**: ERP Integration Architecture for ESG Data Capture [3, 4]*

***Table 3:** AI-Enhanced Supplier Carbon Data Management Capabilities [7, 8]*

AI Application	Functional Capability	Data Processing Technique	Output Benefit
Natural Language Processing	Extraction of carbon data from unstructured documents	Text mining, entity recognition, and semantic analysis	Supplier report automation, data completeness

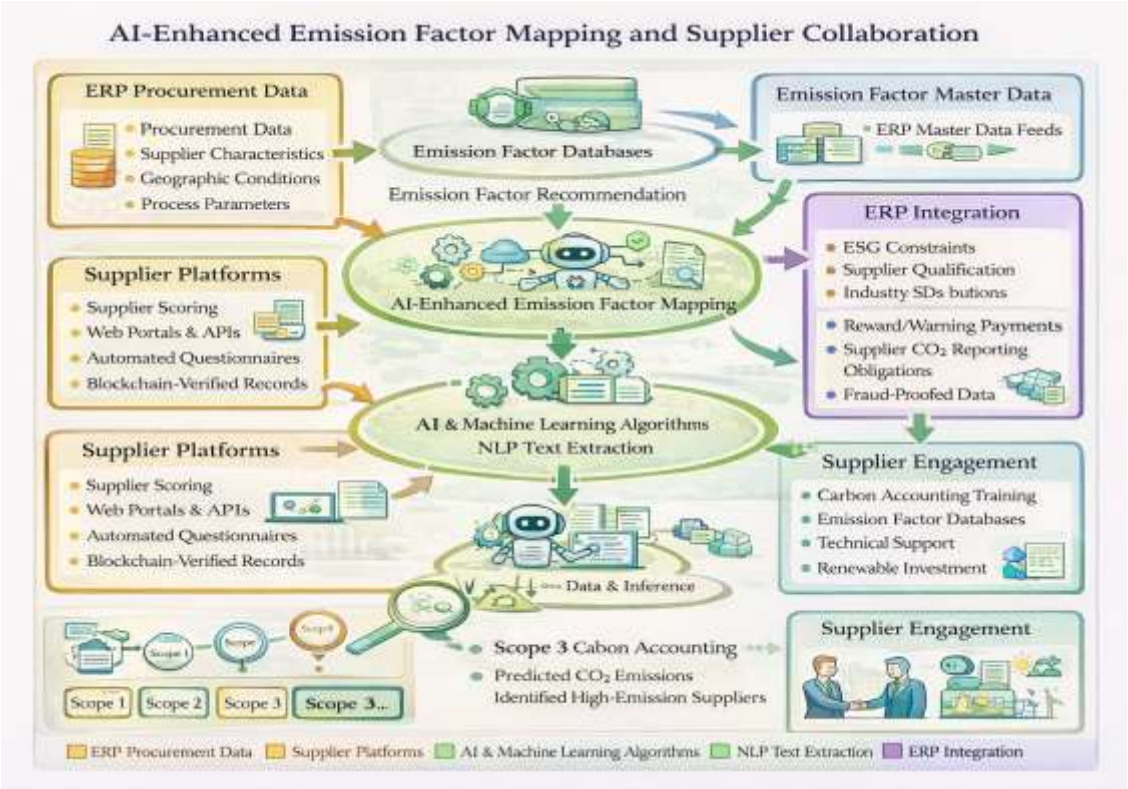

***Figure 2**: AI-Enhanced Emission Factor Mapping and Supplier Collaboration [7, 8]*

Table 4: *Regulatory Frameworks and Strategic ESG Applications [9,* 10]

Regulatory/Strategic Element	Requirements/Objectives	ERP System Support	Business Value
EU Corporate Sustainability Reporting Directive	Mandatory value chain emissions disclosure, double materiality	Automated data aggregation, XBRL report generation, and audit trails	Regulatory compliance, investor confidence
CDP Climate Change Disclosure	Voluntary emissions inventory, target setting, risk assessment	Questionnaire population, scoring optimization, and trend tracking	Investment access, sustainability ratings
Product-Level Carbon Footprinting	SKU-specific cradle-to-grave emissions	Allocation methodologies, LCA integration, and eco-labeling support	Customer differentiation, design optimization
Sustainability-Linked Financing	Performance-based loan terms, green bond eligibility	Covenant monitoring, verification data provision, progress reporting	Favorable financing terms, capital cost reduction

8. Conclusions

Integrating ESG intelligence into ERP enables medical device manufacturers to more effectively measure, manage, and report their Scope 1, 2, and 3 carbon footprints down their Tiers 1 and 2 global supply chains. Removing the data governance and verification barriers that have long prevented Scope 3 carbon data from being considered credible ensures medical device manufacturers can identify the product level visibility which will be required to meet the increasingly rigorous requirements from the European Union's Corporate Sustainability Reporting Directive, healthcare providers' customer decarbonization requests, and investors' ESG information requests that are aligned with the CDP and voluntary climate, water and biodiversity disclosure frameworks. The combination of AI powered emission factor mapping, supplier collaboration platforms and integrated Scope 1, 2, 3 accounting methodologies allows medical device supply chains to move from carbon reporting to carbon management using procurement category, manufacturing and logistics network dashboards to identify carbon hotspots and prioritized capex and opex decarbonization initiatives ranging from renewable energy and process efficiency programs, to material substitution towards lower carbon materials, to supplier collaboration programs driving value chain environmental improvements. Organisations building these ESG capabilities on top of their integrated ERP systems are creating a competitive advantage in healthcare markets, pivoting to value-based care models that create environmental sustainability as a new driver of long-term patient outcomes and planetary health. Medical device manufacturers are leading the charge with systematic decarbonization based on granular supply chain data and a new generation of sustainable healthcare technologies defined by their ESG KPIs. These ESG capabilities are likely to be vital when regulations move to requiring value chain due diligence, product-level disclosure, and financial materiality of climate-related risks across sectors, including healthcare and medical devices. Early movers will be best positioned to use the new operating models and capabilities to support ESG reporting and sustainability in a setting in which the responsibility for health care delivery is coupled with a commitment to the environment.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
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