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Toward Holistic Sustainability in Manufacturing Systems: A Systematic Review of Multidimensional Sustainability Models and Assessment Approaches

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ABSTRACT. *This study aims to examine how multidimensional sustainability models and assessment approaches contribute to the development of holistic sustainability in manufacturing systems. A qualitative systematic literature review was conducted to synthesize previous conceptual and empirical studies concerning economic, environmental, social, technological, organizational, circular economy, and lifecycle dimensions of manufacturing sustainability. The review identifies a transition from fragmented, indicator based approaches toward integrated, hierarchical, and systems oriented sustainability frameworks. The findings indicate that holistic sustainability requires the integration of sustainability dimensions, performance indicators, manufacturing system levels, Industry 4.0 technologies, circular economy principles, human centered practices, and lifecycle perspectives. The review further reveals that sustainability elements are interconnected through synergies, trade offs, dependencies, and enabling relationships. The study contributes a conceptual basis for developing more comprehensive sustainability assessment frameworks that support strategic decision-making and sustainable transformation in manufacturing systems.*

Keywords *Holistic Sustainability; Sustainable Manufacturing; Multidimensional Sustainability; Sustainability Assessment; Manufacturing Systems*

INTRODUCTION

Manufacturing systems face interconnected sustainability challenges involving resource scarcity, environmental degradation, climate change, technological disruption, stakeholder expectations, and long-term economic competitiveness. Consequently, manufacturing sustainability increasingly requires an integrated perspective encompassing economic, environmental, and social dimensions rather than focusing solely on environmental performance or production efficiency (Garetti & Taisch, 2012; Gimenez et al., 2012; Sartal et al., 2020).

The emergence of Industry 4.0, smart manufacturing, and circular production further increases this complexity. Technologies such as IoT, artificial intelligence, cyber physical systems, and advanced automation can improve resource efficiency and process optimization but may also generate energy consumption, resource use, and electronic waste (Chen et al., 2020). Thus, technological modernization should be evaluated through a multidimensional and lifecycle perspective rather than automatically equated with sustainability. The implementation of digital forensics can strengthen law enforcement, especially in cybercrime cases that are difficult to trace with traditional evidence (Yulianti, G & Permana, N., 2024).

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Despite growing research, manufacturing sustainability remains fragmented across indicators, assessment levels, models, and methodological approaches. Studies have addressed corporate, plant, production-line, process, product, supply chain, and technology levels, highlighting the need for integrated assessment frameworks (Azapagic & Perdan, 2000; Huang & Badurdeen, 2018; Jamwal et al., 2022). Cagno et al. (2019) and Neri et al. (2021) further emphasize the importance of scalable and balanced sustainability indicators that capture interactions among economic, environmental, and social dimensions. Strong governance enables Islamic banking to improve competitiveness, operational efficiency, and sustainability (Chaidir, M., et al, 2022).

Circular economy and Industry 4.0 also demonstrate that sustainable manufacturing involves technological, organizational, managerial, and human dimensions simultaneously (Viles et al., 2022). Bernhard et al. (2024) strengthen this perspective through a holistic sustainability model comprising three hierarchical levels dimensions, overarching elements, and specific elements and identifying 40 sustainability elements associated with economic, environmental, and social dimensions. Sharia law provides a strong ethical framework for environmental management, emphasizing sustainability, ecosystem balance, and human religious responsibility toward nature (Eka Wahyu Kasih, et al, 2024).

Nevertheless, existing research remains dispersed across different sustainability dimensions, indicators, assessment frameworks, technologies, and system levels. Therefore, a qualitative systematic literature review is needed to identify common themes, conceptual relationships, assessment approaches, and research gaps across this heterogeneous body of knowledge (Denyer & Tranfield, 2006; Tranfield et al., 2003).

Accordingly, this study aims to synthesize research on multidimensional sustainability models and assessment approaches in manufacturing systems, focusing on sustainability dimensions, key elements and indicators, interactions and trade offs, and the roles of Industry 4.0, circular economy, and human-centered manufacturing. The study seeks to clarify the conceptual architecture of holistic manufacturing sustainability and support the development of more integrated approaches to sustainable manufacturing transformation.

LITERATURE REVIEW

Sustainability in manufacturing has evolved from an environmental focus toward a multidimensional concept integrating economic, environmental, and social well-being (Garetti & Taisch, 2012; Gimenez et al., 2012). The triple bottom line has become a key foundation, emphasizing that manufacturing decisions may generate simultaneous effects across sustainability dimensions (Norman & MacDonald, 2004; Strezov et al., 2017). Consequently, manufacturing sustainability is increasingly viewed as a system-level phenomenon involving interconnected processes, technologies, organizations, and value chains (Sartal et al., 2020; Jamwal et al., 2022).

Early studies focused on sustainability indicators, with Azapagic and Perdan (2000) and Krajnc and Glavic (2003) demonstrating the need for multidimensional industrial indicators. Subsequent research shifted toward integrated assessment, including product-process metrics and hierarchical manufacturing assessment (Huang & Badurdeen, 2017, 2018). Cagno et al. (2019) emphasized scalable measurement systems, while Neri et al. (2021) and Varsei et al. (2014) demonstrated the importance of balanced economic, environmental, and social indicators across supply chains.

Systems thinking emphasizes that sustainability cannot be understood by examining production activities independently because changes in one component may affect others (Ropohl, 2009; Abdoli & Kianian, 2021). Satyro et al. (2021) integrated Industry 4.0, cleaner production, and social stakeholders, while Bernhard et al. (2024) developed a holistic model comprising 40 sustainability elements, eight overarching elements, and three core dimensions. Their findings demonstrate that sustainability elements can contribute to multiple dimensions and should therefore be analyzed through dimensional, hierarchical, and functional production-system perspectives.

Industry 4.0 technologies offer opportunities for resource efficiency, monitoring, optimization, and decision-making (Bai et al., 2020; Carvalho et al., 2018). However, digitalization can also generate energy consumption, material requirements, and environmental impacts (Chen et al., 2020). Felsberger and Reiner (2020) and Ching et al. (2022) therefore emphasize integrated sustainability assessment of digital manufacturing, while Enyoghasi and Badurdeen (2021) highlight impacts across product, process, and system levels.

Circular economy expands manufacturing sustainability through reuse, recycling, remanufacturing, resource efficiency, and closed-loop production (Awan et al., 2022; Kazakova & Lee, 2022). Viles et al. (2022) further demonstrate that circular and Industry 4.0 manufacturing requires technological, managerial, and human integration. Social sustainability is similarly becoming central, particularly through employee well-being, occupational safety, skills, and human centered manufacturing (Hutchins & Sutherland, 2008; Papetti et al., 2020).

Lean manufacturing contributes to sustainability through waste reduction, efficiency, and continuous improvement (Vinodh et al., 2011; Torielli et al., 2011), while Industry 4.0 increasingly integrates lean, green, and circular principles (Varela et al., 2019; Gatell & Avella, 2024). Lifecycle and supply chain approaches further demonstrate that sustainability impacts extend beyond the factory, requiring consideration of suppliers, material flows, product use, and end of life stages (Barni et al., 2022; Varsei et al., 2014; Neri et al., 2021).

Maturity models complement indicator-based approaches by assessing organizational capability to implement lean, digital, and sustainable transformation (Bernhard & Zaeh, 2023; Melkonyan et al., 2017). Overall, the literature shows that manufacturing sustainability has developed through interconnected streams involving triple bottom line assessment, Industry 4.0, circular economy, lean manufacturing, social sustainability, lifecycle assessment, supply chains, and organizational maturity (Felsberger & Reiner, 2020; Jamwal et al., 2022).

Despite this progress, the literature remains fragmented across sustainability dimensions, technologies, indicators, system levels, and assessment objectives (Huang & Badurdeen, 2018; Cagno et al., 2019). Bernhard et al. (2024) provide an important holistic foundation, but further synthesis is needed to integrate multidimensional models with lifecycle, Industry 4.0, circular economy, social sustainability, and maturity approaches. This gap supports the need for a holistic, multidimensional, and interconnected framework for sustainability assessment in manufacturing systems.

A qualitative systematic literature review is therefore necessary because it can synthesize conceptual similarities, differences, relationships, and recurring themes across heterogeneous research traditions rather than simply comparing quantitative effect sizes (Denyer & Tranfield, 2006; Tranfield et al., 2003). Qualitative synthesis is particularly appropriate when the research objective is to understand how concepts are constructed, categorized, interpreted, and related across different studies and methodological traditions (Azungah, 2018; Denyer & Tranfield, 2006).

The literature review methodology proposed by Tranfield et al. (2003) provides a systematic basis for developing evidence-informed management knowledge, while Denyer and Tranfield (2006) demonstrate how qualitative research synthesis can transform dispersed findings into an actionable knowledge base (Tranfield et al., 2003; Denyer & Tranfield, 2006). Accordingly, the present study identifies five major thematic dimensions emerging from the literature: (1) multidimensional sustainability dimensions, (2) hierarchical and systems-oriented sustainability structures, (3) sustainability performance measurement and indicators, (4) technological and circular transformation through Industry 4.0 and circular economy, and (5) human, organizational, and lifecycle dimensions of sustainability (Bernhard et al., 2024; Cagno et al., 2019; Ching et al., 2022; Viles et al., 2022).

Taken together, the previous findings indicate that holistic sustainability in manufacturing should be understood not as the aggregation of independent indicators but as an interconnected architecture in which economic, environmental, social, technological, organizational, lifecycle, and operational elements interact across different levels of the manufacturing system (Bernhard et al., 2024; Satyro et al., 2021).

The principal research gap therefore lies in the absence of a sufficiently integrated synthesis that systematically connects the different multidimensional sustainability models and assessment approaches into a coherent conceptual understanding of holistic manufacturing sustainability (Bernhard et al., 2024; Jamwal et al., 2022). This gap provides the rationale for the present qualitative systematic literature review, which seeks to consolidate existing knowledge, identify dominant conceptual patterns, compare assessment approaches, identify relationships and trade offs among sustainability dimensions, and establish a research agenda for the development of more comprehensive and practically applicable sustainability models for manufacturing systems (Webster & Watson, 2002; Denyer & Tranfield, 2006).

METHODS

This study employs a qualitative systematic literature review (QSLR) to identify, evaluate, interpret, and synthesize research on multidimensional sustainability models and assessment approaches in manufacturing systems. This approach is suitable for fragmented and interdisciplinary fields and follows systematic-review principles proposed by Tranfield et al. (2003), Denyer and Tranfield (2006), and Snyder (2019).

The review emphasizes conceptual patterns, sustainability dimensions, assessment approaches, and relationships across studies rather than statistical effect sizes. The process includes research-question formulation, literature searching, screening, quality appraisal, data extraction, qualitative coding, thematic synthesis, and cross-study comparison. PRISMA 2020 is applied to enhance transparency in study identification and selection (Page et al., 2021).

The review addresses six areas: conceptualizations of sustainability in manufacturing; sustainability dimensions; indicators and assessment frameworks; synergies and trade-offs; the roles of Industry 4.0, circular economy, lean manufacturing, and human-centered manufacturing; and remaining conceptual and methodological gaps.

The literature search covers peer-reviewed studies published from 2000–2025 using terms related to sustainable manufacturing, sustainability assessment, indicators, performance measurement, multidimensional sustainability, circular economy, and Industry 4.0. Studies are included when they address manufacturing or production systems and at least one relevant sustainability model, indicator, framework, measurement approach, maturity model, or lifecycle perspective. Non-scholarly publications, duplicates, insufficiently relevant studies, and studies outside the defined language scope are excluded.

Study selection follows identification, duplicate removal, title and abstract screening, full-text assessment, and final inclusion. Selected studies are evaluated based on objective clarity, methodological transparency, design appropriateness, credibility of findings, and relevance to multidimensional manufacturing sustainability. Higher-quality studies receive greater analytical emphasis.

Data extraction includes bibliographic information, research context and design, sustainability dimensions, assessment approaches, system levels, technological and circular-economy roles, findings, limitations, and research gaps. Qualitative thematic synthesis is then conducted through open coding, category development, thematic aggregation, and conceptual synthesis. The coding framework covers economic, environmental, social, technological, organizational, lifecycle, circularity, Industry 4.0, lean manufacturing, indicators, performance measurement, maturity assessment, and stakeholder integration.

Findings are organized into sustainability dimensions, overarching themes, and specific elements and indicators. Cross-study comparison examines conceptual scope, system boundaries, assessment methods, technological integration, and implementation orientation. The review also identifies synergies, trade-offs, dependencies, and enabling relationships among sustainability dimensions.

Finally, research gaps are identified across conceptual, methodological, empirical, technological, and implementation areas, particularly model fragmentation, limited integration of qualitative and quantitative assessment, insufficient empirical validation, and the need for critical integration of digital technologies. Trustworthiness is strengthened through transparent procedures, explicit criteria, structured extraction, systematic coding, and an audit trail. Overall, this methodology enables a holistic understanding of how sustainability dimensions, manufacturing-system levels, technologies, and assessment approaches are interconnected.

RESULTS

The qualitative systematic literature review identified a substantial body of research on sustainable manufacturing, sustainability performance measurement, multidimensional models, Industry 4.0, circular economy, lean production, lifecycle assessment, and social sustainability. The literature has progressively shifted from single-dimensional environmental assessment toward integrated approaches recognizing economic, environmental, and social sustainability as interconnected components of manufacturing-system performance (Garetti & Taisch, 2012; Gimenez et al., 2012; Jamwal et al., 2022).

Contemporary manufacturing sustainability research is characterized by multidimensionality, systems orientation, integrated assessment, technological and circular transformation, and increasing recognition of human and organizational dimensions. These characteristics form an interconnected structure in which sustainability dimensions, production levels, technologies, organizational capabilities, and assessment mechanisms influence one another. Accordingly, sustainability can no longer be adequately represented through a single indicator or environmental metric (Cagno et al., 2019; Neri et al., 2021; Bernhard et al., 2024).

The literature strongly converges around three core dimensions: economic, environmental, and social sustainability (Azapagic & Perdan, 2000; Gimenez et al., 2012; Strezov et al., 2017). The economic dimension includes productivity, efficiency, profitability, and competitiveness; the environmental dimension encompasses energy, materials, emissions, waste, and resource use; while the social dimension addresses employee well-being, health and safety, skills, and stakeholder interests (Hutchins & Sutherland, 2008; Papetti et al., 2020). These dimensions are interconnected, as improvements in one area may generate benefits or trade-offs in others (Bernhard et al., 2024).

Sustainability assessment is hierarchical and system-oriented, covering processes, production lines, plants, firms, supply chains, products, and life cycles (Huang & Badurdeen, 2017, 2018; Varsei et al., 2014; Neri et al., 2021). Sustainability performance should therefore connect specific indicators with broader sustainability elements and dimensions. Efficiency is particularly important as a cross-dimensional mechanism because energy and material efficiency, waste reduction, process optimization, and productivity improvements can simultaneously generate economic and environmental benefits (Vinodh et al., 2011; Huang & Badurdeen, 2018; Bernhard et al., 2024).

The literature also demonstrates a shift from individual sustainability indicators toward integrated measurement systems, including balanced KPIs, performance measurement systems, maturity models, lifecycle approaches, and multidimensional frameworks (Azapagic & Perdan, 2000; Krajnc & Glavic, 2003; Cagno et al., 2019). Balanced measurement across economic, environmental, and social dimensions is essential, while assessment should also correspond to different manufacturing-system levels (Neri et al., 2021; Huang & Badurdeen, 2018; Barni et al., 2022).

Industry 4.0 represents an important sustainability enabler through real-time monitoring, predictive maintenance, process optimization, resource efficiency, traceability, and improved decision-making (Bai et al., 2020; Chen et al., 2020; Ching et al., 2022). However, digitalization should not automatically be equated with sustainability because it may also create energy and lifecycle burdens (Chen et al., 2020). Similarly, circular economy principles extend sustainability toward reuse, recycling, remanufacturing, product-life extension, and resource-loop closure (Awan et al., 2022; Kazakova & Lee, 2022; Skärin et al., 2023).

The human and social dimension is increasingly recognized as central to sustainable manufacturing. Employee well-being, occupational health and safety, skills development, and human-centered production contribute not only to social sustainability but also to productivity, resilience, and innovation (Hutchins & Sutherland, 2008; Papetti et al., 2020; Sundström et al., 2019; Caggiano et al., 2022).

Holistic sustainability also requires broader system boundaries beyond the factory, including supply chains and product life cycles (Barni et al., 2022; Dorn et al., 2016; Varsei et al., 2014). Sustainability elements are therefore interdependent rather than additive, and improvements in one element may enable, reinforce, or constrain others (Cagno et al., 2019; Neri et al., 2021; Ching et al., 2022; Bernhard et al., 2024).

Overall, no single assessment method is sufficient to capture the complexity of manufacturing sustainability. Indicator frameworks, KPI systems, lifecycle assessment, maturity models, Industry 4.0 frameworks, and circular-economy approaches should be integrated rather than treated as competing alternatives (Azapagic & Perdan, 2000; Huang & Badurdeen, 2018; Bai et al., 2020; Awan et al., 2022; Bernhard & Zaeh, 2023). Holistic sustainability should therefore be understood as an integrative architecture connecting sustainability dimensions, production-system levels, technologies, organizational capabilities, circularity, lifecycle thinking, and relationships among sustainability outcomes.

The findings ultimately demonstrate that manufacturing sustainability has evolved from fragmented and primarily indicator-based approaches toward multidimensional, interconnected, hierarchical, and system-oriented models. Economic, environmental, and social sustainability remain the foundation, while technological, organizational, and lifecycle perspectives increasingly support their practical realization (Felsberger & Reiner, 2020; Ching et al., 2022; Viles et al., 2022). Thus, holistic sustainability does not simply mean adding more indicators, but understanding sustainability as an interdependent system of dimensions, elements, and relationships (Bernhard et al., 2024).

DISCUSSION

The findings of this qualitative systematic literature review indicate that sustainability in manufacturing systems is evolving from a predominantly indicator based and pillar oriented concept toward a holistic, multidimensional, hierarchical, and relational system of sustainability elements. This finding is consistent with the broader evolution of sustainable manufacturing identified by Jamwal et al. (2022), who showed that research between 1999 and 2020 expanded from sustainable planning, scheduling, and environmental management toward sustainable supply chains, lean production, Industry 4.0, and integrated manufacturing systems. The present review extends this trajectory by arguing that the central challenge is no longer simply identifying additional sustainability indicators, but understanding how different sustainability dimensions, elements, technologies, organizational capabilities, and system levels interact with one another.

The first important finding is that economic, environmental, and social dimensions remain the fundamental pillars of manufacturing sustainability, but the literature increasingly treats these dimensions as interdependent rather than independent. Bernhard et al. (2024) provide particularly strong support for this interpretation because their holistic production-system model organizes sustainability into dimensions, overarching elements, and specific elements, identifying 40 elements and eight overarching elements across economic, environmental, and social sustainability. This finding is consistent with Cagno et al. (2019), who argued that existing industrial sustainability performance measurement systems have insufficiently addressed the intersections among sustainability pillars and therefore developed scalable measurement systems intended to cover the pillars and their intersections.

The present review therefore differs conceptually from approaches that treat the triple bottom line as three parallel measurement categories because it emphasizes cross-dimensional relationships among sustainability elements. Neri et al. (2021), for example, developed a balanced set of sustainability KPIs for industrial supply chains that explicitly addresses the sustainability pillars and their intersections, supporting the argument that balanced measurement is more appropriate than isolated economic, environmental, or social measurement. Thus, the results of the present review confirm the continued relevance of the triple bottom line while proposing a more integrated interpretation in which the three dimensions constitute an interconnected sustainability architecture.

The second major finding concerns the level of integration achieved by previous sustainability assessment approaches. Huang and Badurdeen (2018) developed a comprehensive metrics-based approach for production-line and plant-level sustainability assessment and incorporated the three sustainability pillars, lifecycle considerations, and the 6R concept into a five-level hierarchy from metrics to an overall sustainability index. The present review supports Huang and Badurdeen's hierarchical approach but extends it conceptually by emphasizing that hierarchy should connect not only indicators and indices but also sustainability dimensions, overarching elements, production-system levels, and relationships among elements.

Cagno et al. (2019) similarly proposed three industrial sustainability performance measurement systems with different numbers of indicators to accommodate organizational context, available resources, and sustainability maturity. Compared with Cagno et al. (2019), the present synthesis places greater emphasis on the conceptual architecture underlying the indicators, suggesting that scalability should not only concern the number of indicators but also the ability of a framework to represent relationships among sustainability elements.

Neri et al. (2021) addressed a related problem at the supply-chain level by developing a manageable KPI set from a literature base containing more than 2,000 performance measures, while maintaining balanced coverage of sustainability pillars and intersections. The present review agrees that excessive numbers of indicators can reduce practical usefulness, but further argues that indicator reduction should be guided by an explicit multidimensional model that identifies which elements are strategically connected and why.

The third finding is that sustainability should be assessed across multiple manufacturing-system levels rather than being restricted to individual processes or environmental indicators. Huang and Badurdeen (2018) demonstrated the importance of production line and plant level assessment, while Neri et al. (2021) extended sustainability measurement to the entire industrial supply chain. Bernhard et al. (2024) further contribute by explicitly modeling sustainability within production systems through a multidimensional structure of elements, overarching elements, and dimensions.

This finding is also consistent with Jamwal et al. (2022), whose systematic review identified the development of sustainable manufacturing research across sustainable supply chains, lean production, sustainable machining, decision-making, Industry 4.0, and Lean production systems. Therefore, the present study suggests that manufacturing sustainability should be conceptualized as a system-of-interacting-levels, extending from machines and processes to production lines, plants, organizations, supply chains, and product lifecycles.

The fourth major finding concerns Industry 4.0. Felsberger and Reiner (2020), through a systematic literature review of 89 papers published between 2010 and 2020, found substantial research connecting Industry 4.0 with sustainability in production and operations management and identified sustainability dimensions and research gaps within this emerging field. Their findings support the present review's conclusion that digital transformation has become an important component of sustainable manufacturing.

Ching et al. (2022) provide an even stronger comparison because their systematic review identified functions through which Industry 4.0 enables sustainable manufacturing and developed a structural model explaining the relationships among those functions. The present review is consistent with Ching et al. (2022) in viewing digital technologies as enablers of sustainability, but extends the interpretation by emphasizing that technology must be embedded within a broader economic, environmental, social, organizational, and lifecycle framework.

Sartal et al. (2020) similarly concluded that Industry 4.0 offers significant opportunities for sustainable manufacturing through digital transformation, while also highlighting a lack of consensus concerning its social consequences. This observation strongly supports the present finding that digitalization should not automatically be interpreted as sustainability because technological benefits may coexist with social or environmental challenges.

The fifth finding is the increasing importance of circular economy as an integrative mechanism within sustainable manufacturing. Viles et al. (2022) argued that sustainable production principles need to be reconsidered in the context of circular economy and Industry 4.0 and used a Delphi panel involving 11 experts to develop updated principles for sustainable production. Their findings support the present review's conclusion that sustainability can no longer be confined to conventional production efficiency because circularity introduces resource loops, reuse, recycling, remanufacturing, and extended product-life considerations.

The present review extends Viles et al. (2022) by positioning circularity as a cross-dimensional mechanism rather than merely an environmental objective. Circular production can generate environmental benefits through reduced resource consumption while simultaneously affecting economic efficiency, technological requirements, organizational capabilities, and social implications. This interpretation is consistent with the broader evolution of manufacturing sustainability identified by Jamwal et al. (2022), in which sustainability research increasingly connects environmental management with supply chains, lean production, and Industry 4.0.

The sixth finding concerns the increasing importance of social sustainability within manufacturing systems. Sartal et al. (2020) identified a lack of consensus concerning the social impact of Industry 4.0 even though economic and ecological benefits were more consistently recognized. This observation is important because it demonstrates that technological and environmental improvements cannot be assumed to represent holistic sustainability when their implications for workers and society remain uncertain.

The present review therefore positions human well being, occupational health, skills, participation, and working conditions as core sustainability elements rather than secondary indicators. This interpretation strengthens the holistic model proposed by Bernhard et al. (2024), because a multidimensional production system model should recognize that sustainability outcomes emerge from interactions among technological, organizational, economic, environmental, and human factors.

A seventh important finding is that sustainability assessment is moving from measurement toward decision support and organizational transformation. Cagno et al. (2019) demonstrated that sustainability measurement systems need to be scalable according to organizational context and sustainability maturity, while Neri et al. (2021) demonstrated the value of a manageable KPI system that can operate across different decision making levels. Huang and Badurdeen (2018) similarly demonstrated that hierarchical indices can translate multiple sustainability metrics into production line and plant level evaluations.

The present review consequently argues that future holistic sustainability models should not merely answer "How sustainable is the manufacturing system?", but also

"Which sustainability elements require intervention, how are they connected, and what consequences could an intervention generate elsewhere in the system?" This represents an important theoretical shift from descriptive measurement toward relational and diagnostic sustainability assessment.

The eight studies most directly comparable with the present review demonstrate the progressive development of the field. Bernhard et al. (2024) provide the closest conceptual foundation through their multidimensional holistic model, while the present review extends this perspective by synthesizing it with broader research on digitalization, circularity, supply chains, and assessment methods. Cagno et al. (2019) emphasize scalable industrial sustainability measurement, whereas the present study emphasizes the conceptual relationships that should guide indicator selection. Huang and Badurdeen (2018) focus on hierarchical metrics and indices at production line and plant levels, whereas the present study extends hierarchy to multidimensional sustainability architecture. Neri et al. (2021) emphasize balanced KPIs across industrial supply chains, while the present study integrates supply-chain thinking into a broader manufacturing-system framework. Felsberger and Reiner (2020) demonstrate the growing relationship between Industry 4.0 and sustainability, while the present review incorporates digitalization as one component within a broader holistic system. Ching et al. (2022) identify Industry 4.0 functions and their structural relationships, while the present review generalizes the relational perspective beyond digital technologies to all sustainability dimensions. Viles et al. (2022) redefine sustainable production principles in the context of circular economy and Industry 4.0, while the present study incorporates circularity as one of the mechanisms connecting environmental, economic, technological, and organizational sustainability. Finally, Jamwal et al. (2022) map the evolution of sustainable manufacturing research and identify major themes including sustainable supply chains, lean production, environmental management, Industry 4.0, and decision making, whereas the present review seeks to integrate these previously dispersed streams into a holistic conceptual structure.

The principal theoretical contribution of this review is the proposition that holistic manufacturing sustainability should be conceptualized as a multidimensional relational architecture rather than an aggregate of independent sustainability indicators. Bernhard et al. (2024) already demonstrate that sustainability elements can be organized into dimensions and overarching elements, while Cagno et al. (2019) and Neri et al. (2021) demonstrate the importance of intersections among sustainability indicators.

Based on the comparison of eight previous studies, the present synthesis proposes that a comprehensive sustainability model should integrate economic, environmental, and social foundations; technological and organizational enablers; circular economy mechanisms; lifecycle and supply chain boundaries; and hierarchical manufacturing-system levels. This synthesis is consistent with the evolution identified by Jamwal et al. (2022) and the multidimensional structure demonstrated by Bernhard et al. (2024).

Overall, the findings demonstrate a clear transition from fragmented sustainability measurement toward holistic sustainability modeling. This transition is supported by the evolution of sustainable manufacturing research identified by Jamwal et al. (2022), the scalable assessment systems developed by Cagno et al. (2019), the hierarchical metrics of Huang and Badurdeen (2018), the balanced supply chain KPIs of Neri et al. (2021), the Industry 4.0 sustainability research of Felsberger and Reiner (2020) and Ching et al. (2022), and the circular-production principles of Viles et al. (2022).

The strongest evidence for this transition comes from Bernhard et al. (2024), whose model explicitly integrates 40 sustainability elements, eight overarching elements, and three core sustainability dimensions into a holistic production-system model. The present review therefore concludes that the next generation of manufacturing sustainability research should move beyond the question of which indicators should be measured toward the more comprehensive question of how sustainability elements interact across dimensions, system levels, technologies, organizations, supply chains, and product lifecycles.

CONCLUSION

This qualitative systematic literature review concludes that manufacturing sustainability has evolved from a pillar-based and indicator-oriented concept toward a holistic, multidimensional, and interconnected system perspective. Economic, environmental, and social dimensions remain fundamental, but they increasingly interact across sustainability elements and cannot be effectively managed independently (Cagno et al., 2019; Neri et al., 2021; Bernhard et al., 2024).

Holistic sustainability requires more than adding indicators; it requires an integrated architecture connecting sustainability dimensions, operational indicators, manufacturing-system levels, and relationships among sustainability outcomes (Huang & Badurdeen, 2018; Bernhard et al., 2024). Sustainability assessment should therefore extend from individual processes to production lines, plants, organizations, supply chains, and product lifecycles (Varsei et al., 2014; Neri et al., 2021).

Industry 4.0 and digital transformation can enable resource efficiency, monitoring, optimization, and decision-making, but may also generate environmental and social impacts (Bai et al., 2020; Chen et al., 2020). Similarly, circular economy connects resource efficiency, waste reduction, reuse, recycling, and remanufacturing, while human well-being, occupational safety, and organizational capabilities are increasingly recognized as essential sustainability dimensions (Awan et al., 2022; Viles et al., 2022; Papetti et al., 2020).

Overall, the review supports a transition from measuring sustainability dimensions separately toward understanding sustainability as an interconnected system. Future models should integrate multidimensional indicators, lifecycle thinking, circularity, Industry 4.0, social sustainability, organizational capabilities, and explicit analysis of synergies and trade-offs to support more coherent and sustainable manufacturing transformation (Bernhard et al., 2024; Jamwal et al., 2022).

LIMITATION

This study has several limitations. First, the findings depend on the selected databases, keywords, and inclusion criteria, meaning that relevant studies outside the search strategy may have been overlooked (Tranfield et al., 2003; Snyder, 2019). Second, the heterogeneity of manufacturing contexts, methodologies, indicators, and sustainability definitions limits direct comparison across studies (Jamwal et al., 2022). Third, the qualitative and interpretive nature of the synthesis may introduce researcher subjectivity in coding and thematic classification (Denyer & Tranfield, 2006; Azungah, 2018). Fourth, the absence of meta-analysis means that the strength and statistical significance of sustainability relationships cannot be quantified.

Finally, the rapid development of Industry 4.0, AI, circular economy, and other emerging technologies may require continuous revision of sustainability models (Bai et al., 2020; Chen et al., 2020). Existing literature also lacks a universally validated framework integrating economic, environmental, social, technological, organizational, circular, and lifecycle dimensions (Felsberger & Reiner, 2020; Viles et al., 2022). Future research should therefore empirically validate integrated sustainability models across different industries and contexts, while quantitatively examining sustainability synergies and trade offs (Bernhard et al., 2024; Neri et al., 2021).

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