Chips and Challenges: An Integrative Review on Sustainability and Risk Management in Semiconductor Supply Chains

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ABSTRACT

The semiconductor industry, foundational to modern technology, faces critical sustainability and risk challenges arising from resource-intensive operations, concentrated production geographies and recurrent disruptions. Fabrication plants consume extraordinary volumes of water and energy, while geopolitical tensions, material shortages, and demand volatility continue to destabilize global supply networks. These vulnerabilities underscore the need for integrated approaches to sustainable supply chain risk management (SSCRM). This study conducts the first integrative review at the intersection of sustainable supply chain management (SSCM) and supply chain risk management (SCRM) in the semiconductor context. Drawing on over 1,500 studies screened from *UTD24* (University of Texas at Dallas) and *SCM* (Supply Chain Management) journal lists (2010-2024), we identify 46 seminal works and analyze them through four frameworks: ESG (Environmental, Social, Governance), Triple Bottom Line (TBL), Triple A (Agility, Adaptability, Alignment), and Triple A&R (adding Robustness, Resilience, Realignment). Our synthesis highlights six interconnected research imperatives: AI-enabled transparency and predictive analytics, power asymmetries in buyer–supplier relationships, geopolitical sustainability trade-offs, collaborative governance models, the bullwhip effect's impact on resilience and sustainability, and the application of Triple A&R principles to semiconductor operations. By synthesizing insights across these themes, we propose targeted research questions that bridge theoretical constructs with semiconductor-specific operational challenges. Our findings underscore the urgency of adopting integrated SSCRM approaches to

fortify the industry's resilience, innovation, and long-term sustainability against escalating global disruptions.

Keywords: Sustainability, Risk, Sustainable Supply Chain Risk Management, Semiconductor Industry, Resilience

INTRODUCTION

Semiconductors form the backbone of modern technology, powering everything from smartphones to electric vehicles, with U.S. sales surging to $264 billion in 2023 alone (Ravi, 2024). Yet this critical, trillion-dollar industry operates on razor-thin margins of resilience. Geographically concentrated semiconductor supply chains remain vulnerable to fires, geopolitical shocks, and material shortages. Such disruptions have cascaded across automotive, healthcare, and electronics sectors, incurring losses exceeding €400 million per incident and costing the industry $210 billion in 2021 (Harland, 2021; J. Lee, 2023). These crises also exacerbate sustainability challenges, as production restarts and rushed logistics accelerate waste and carbon emissions. These sustainability pressures are particularly critical given that semiconductor manufacturing alone contributes nearly 10% of global industrial fluorinated greenhouse gas (GHG) emissions (Jacobs et al., 2022; Khademi & Eksioglu, 2018).

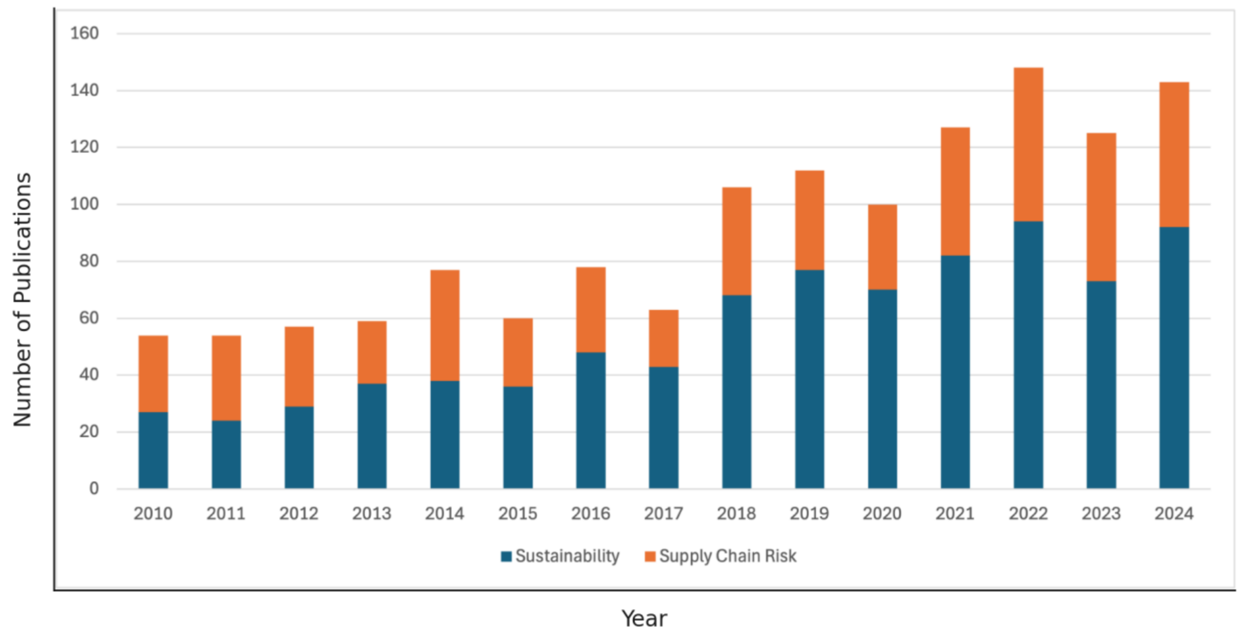
The semiconductor industry is organized across several firm types. Fabless firms such as Qualcomm and NVIDIA focus on chip design but outsource manufacturing. Foundries such as the Taiwan Semiconductor Manufacturing Company (TSMC) specialize in wafer fabrication for external clients, producing over 90% of the world's most advanced semiconductor wafers. Integrated device manufacturers (IDMs) such as Intel or Samsung combine design and fabrication in-house, while outsourced assembly and test (OSAT) providers such as the

Advanced Semiconductor Engineering (ASE) handle packaging and testing. Together, these firms form an interdependent global network where risks and sustainability challenges propagate rapidly.

While Sustainable Supply Chain Management (SSCM) and Supply Chain Risk Management (SCRM) research has grown exponentially, visually captured in Figure 1's 2010-2024 publication trends, their integration into SSCRM remains significantly underexplored within semiconductor-specific contexts. SSCRM combines environmental responsibility, social equity, and operational resilience (Araullo, 2024). However, semiconductor applications of SSCRM lack systematic analysis, particularly given the industry's extreme water and energy intensity, conflict-mineral dependencies, and geopolitical weaponization of exports. An average chip manufacturing facility uses over 10 million gallons of water daily which is equivalent to the water usage of 33,000 US households every day (James, 2024). To our knowledge, no comprehensive synthesis bridges established frameworks (ESG, TBL, Triple A, Triple A&R) with semiconductor Sustainable Supply Chain Risk Management (SSCRM) challenges, which is a critical gap as global semiconductor chip demand surges (Ravi, 2024).

Figure 1

Publication Frequency in the Sustainability and Supply Risk Literatures from the UTD and SCM List Journals

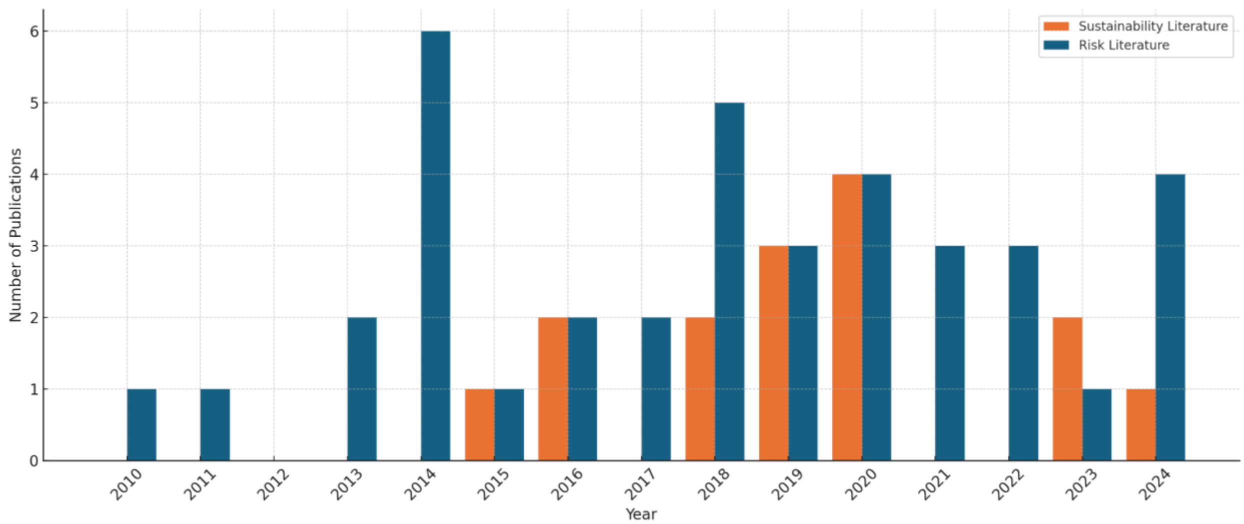


Source: Authors

Semiconductors demand urgent, specialized focus. Unlike other industries, their supply chains face unique triple pressures: resource intensity (e.g., ultrapure water, rare earth metals), geopolitical risks (e.g., export controls on gallium), and explosive demand growth driven by AI, electric vehicles, and 5G/6G technologies. With $2.3 trillion earmarked for global semiconductor infrastructure through 2032 (Ravi, 2024), how capacity is built now will determine whether this expansion fuels sustainable progress or perpetuates systemic fragility. This paper addresses this imperative by synthesizing 46 seminal studies (2010-2024) from leading *UTD24* and *SCM* journals (please see Appendix for the list of journals), extracting semiconductor-specific insights from broader SSCM and SCRM literature (Figure 2). We apply four pivotal frameworks: ESG, TBL, Triple A, and Triple A&R, to dissect critical gaps and propose future research directions. These research directions include AI's role in predicting shortages and ethical lapses, bullwhip effects destabilizing sustainable material sourcing, geopolitical fractures amplifying environmental and social risks, power rebalancing in buyer-supplier negotiations over conflict minerals, and Triple A&R strategies fortifying green fab resilience.

Figure 2

Final Publication Frequency with a Focus on the Semiconductor Industry



Source: Authors

By tethering these frameworks to semiconductor realities, this review provides a roadmap to transform trillion-dollar investments into engines of enduring stability, ensuring the chips powering humanity's future do not come at the cost of sustainability or supply chain resilience. The remainder of this paper is structured as follows. The Background section introduces the key frameworks of SSCM and SCRM that inform our analysis. The Findings section synthesizes insights from the reviewed literature, identifying both explored themes and underexplored gaps across SSCM, SCRM, and SSCRM. The Discussion builds on these gaps by proposing six future research questions that integrate sustainability and risk management perspectives. Finally, the

Conclusion section highlights the study's boundaries and outline directions for advancing scholarship and practice in semiconductor supply chains.

BACKGROUND

Across the two literature streams of SSCM and SCRM, there are different types of frameworks that are especially critical for industries facing complex environmental, social, and operational pressures: ESG and TBL frameworks for SSCM, and Triple-A and Triple A&R frameworks for SCRM. The semiconductor industry, characterized by high resource intensity, geopolitical supply chain vulnerabilities, and stringent regulatory scrutiny, must adopt these structured frameworks to enhance sustainability, resilience, and combat risk. Next, we examine these frameworks (summarized in Table 1) and their applicability to semiconductor supply chains.

Sustainability

ESG Framework

The ESG framework integrates Environmental, Social, and Governance principles into supply chain decision-making, emphasizing sustainability alongside profitability (Gabler et al., 2023; Singhania & Saini, 2023). In the Environmental dimension, companies prioritize reducing carbon footprints, investing in renewable energy, developing water conservation and recycling systems, and minimizing waste, which can lower regulatory risks and operational costs (Friede et al., 2015). The Social dimension highlights fair labor practices, workplace safety, and community engagement, which improve supplier relationships and help protect brand reputation in regions where labor practices are under scrutiny (Orlitzky et al., 2003). The Governance dimension ensures ethical decision-making, transparency, and compliance through structured anti-corruption policies, conflict mineral reporting, and monitoring (Baldini et al., 2018; Khamisu et al., 2024). Applied to semiconductors, ESG helps mitigate regulatory risks and reputational damage, while enabling firms to respond to growing investor and consumer expectations for sustainable operations (Gabler et al., 2023).

TBL Framework

The TBL framework broadens corporate performance measurement from a narrow focus on profit to a balanced assessment of People, Planet, and Profit, offering a holistic approach to sustainable supply chains (Miller, 2020; Wilhelm et al., 2016). The People dimension promotes equitable wages, diversity, ethical labor practices, and investments in local communities, mitigating labor violation risks and strengthening social license to operate (Elkington, 1997). The Planet dimension focuses on eco-efficiency, adoption of circular economy principles, greenhouse gas emission reductions, and recycling of rare minerals such as cobalt and tantalum, which are central to chip production (Cohen et al., 2022). The Profit dimension ensures that sustainability initiatives remain economically viable, aligning environmental and social investments with cost savings from energy efficiency and consumer demand for ethically produced technology (Miller, 2020). For semiconductors, TBL provides a framework to align long-term competitiveness with societal expectations and financial success with stakeholder expectations regarding sustainability, particularly for firms reliant on ethically sourced materials like silicon and cobalt (Elkington, 1997).

Insert Table 1 Here

Supply Chain Risk and Resilience

Triple-A Framework

The Triple-A framework enhances supply chain resilience through Agility, Adaptability, and Alignment (Kovács & Falagara Sigala, 2021). The Agility dimension enables rapid responses to unexpected shocks such as sudden demand surges or supplier failures, allowing firms to minimize costly downtime (Lee & See, 2004). The Adaptability dimension addresses structural, long-term shifts in markets and technology, for example, adjusting to new export regulations, shifting to alternative raw materials like gallium nitride, or rebalancing geographic supply footprints. The Alignment dimension promotes cooperation among stakeholders, ensuring that suppliers, original equipment manufacturers (OEMs), and governments share goals and metrics. For semiconductors, the Triple-A framework directly mitigates risks arising from fragmented global supply networks, where alignment failures or slow responses can have disproportionate impacts on production continuity (Kovács & Falagara Sigala, 2021).

Triple A&R Framework

The Triple A&R framework extends Triple-A by adding Robustness, Resilience, and Realignment to better address today's highly uncertain environments (Cohen & Kouvelis, 2021; Lee & See, 2004). The Robustness dimension emphasizes proactive preparation, including buffer inventories, dual sourcing strategies, and diversification of wafer production across multiple regions. The Resilience dimension underscores the ability to recover quickly from disruptions, as demonstrated during the COVID-19 pandemic when firms with regional fabrication networks restored operations faster than those dependent on a single geography. The Realignment dimension ensures that supply chains evolve alongside shifting global priorities such as decarbonization, diversity, and regulatory compliance, allowing firms to integrate sustainability with strategic reconfiguration. Crucially, Triple A&R explicitly prepares firms for black swan events (rare, high-impact disruptions like the 2011 Fukushima earthquake or sudden export bans on rare gases) that can destabilize global semiconductor supply chains overnight. For this industry, where resilience is as critical as cost efficiency, Triple A&R offers a robust roadmap for simultaneously managing risk and meeting sustainability goals. By extending the Triple-A framework with the R dimensions, it equips semiconductor firms to withstand systemic shocks and align long-term resilience with sustainability imperatives.

Towards an Integrated SSCRM Approach

While ESG, TBL, Triple-A, and Triple A&R offer distinct frameworks for sustainability and risk management, their integration can create a holistic Sustainable Supply Chain Risk Management (SSCRM) strategy for the semiconductor industry. By combining ESG's stakeholder focus, TBL's balanced metrics, Triple A's agile strategies, and Triple-A&R's operational resilience, semiconductor firms can navigate disruptions while advancing sustainability, a critical imperative in an era of climate change and geopolitical volatility.

METHODOLOGY

To integrate research from sustainability and supply chain risk literatures into the context of semiconductors, we conducted extensive searches on Google Scholar and corroborated with Web of Science, two widely recognized academic databases. The keyword searches included combinations such as "sustainable supply chain" with "semiconductor" and "supply chain risk" with "semiconductor" or "microelectronic" along with other iterations of these phrases. Figure 3 illustrates the overall search and screening process. Journals targeted for inclusion were drawn from the *UTD24* List (24 journals) and the *SCM* Journal List (8 journals), with 5 journals appearing on both lists. These journals were selected because they are widely recognized as high-impact and influential outlets within the supply chain management discipline, ensuring that this review draws from the most reputable scholarly sources. The articles were screened and filtered based on relevance to sustainability, supply chain risk, and the semiconductor industry.

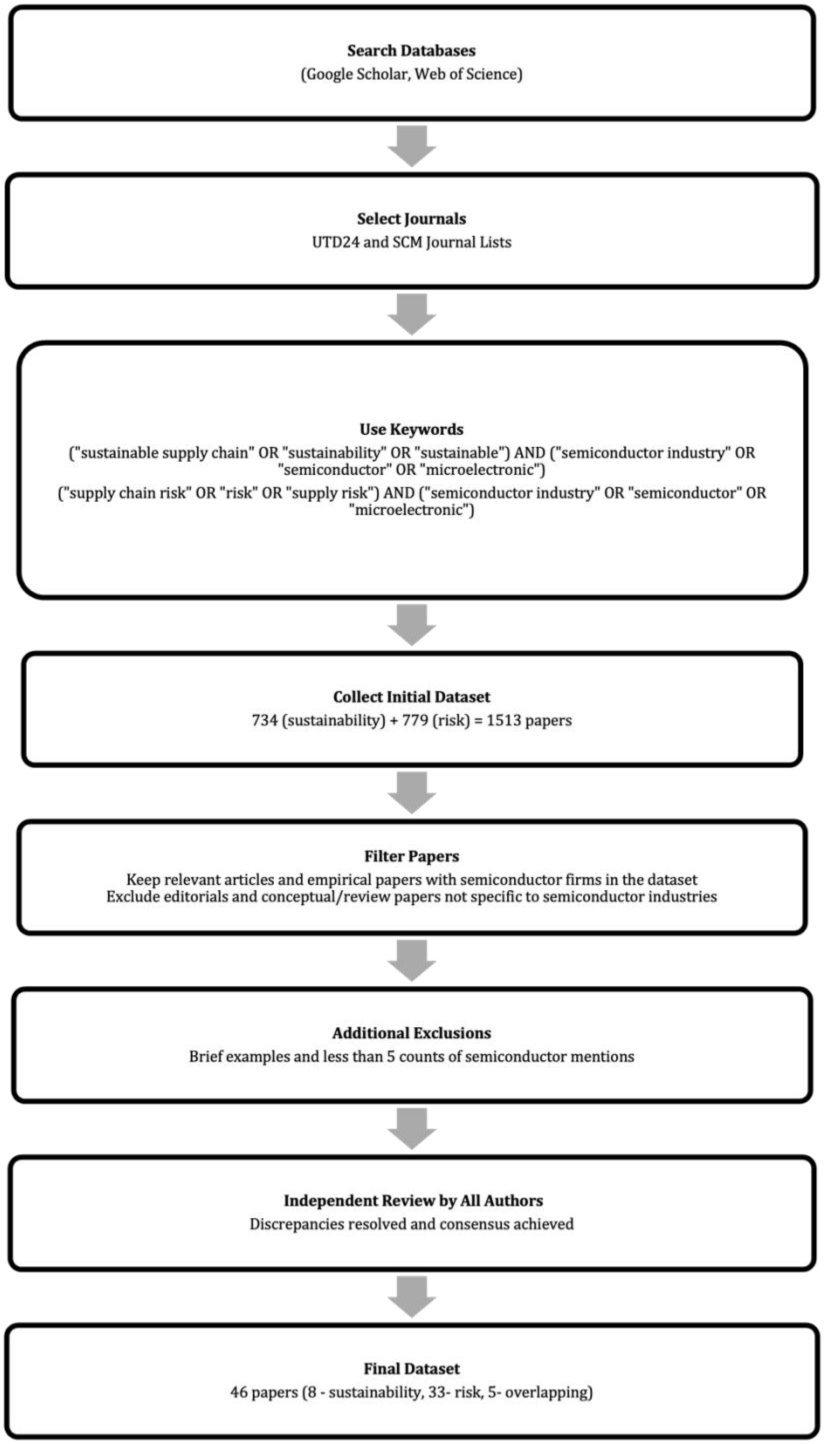
The initial dataset comprised 734 papers on SSCM and 781 papers on SCRM, leading to a total of 1,513 papers reviewed across both themes. Next, papers such as editorial notes, conceptual pieces and literature reviews that did not apply the context of the semiconductor industry were eliminated. A rigorous assessment of each article was then conducted to determine whether its content or empirical analysis aligned with the study's objectives and the context of the semiconductor industry. In some cases, papers were accepted if the semiconductor firms appeared in the datasets used for analysis, even though the word "semiconductor" (or its iterations) was mentioned only two or three times. This step resulted in the exclusion of 701 papers (out of 734) on SSCM and 693 papers (out of 781) on SCRM.

An additional 18 papers in SSCM and 43 papers in SCRM were eliminated because they mentioned semiconductors only briefly, either in a few sentences or as examples, without establishing a substantial focus on the semiconductor industry. To minimize subjectivity in this evaluation, all authors independently read and assessed all articles. Discrepancies were resolved through discussions, ensuring consensus on whether each paper should be included in the review.

Insert Table 2 Here

Figure 3

Process Flowchart for Reviewing Articles



Source: Authors

This process resulted in the selection of 46 articles: 8 in SSCM, 33 in SCRM, and 5 in the overlapping SSCRM domain, published between 2010 and 2024. Table 2 lists the article count by journal for the three SSCM, SCRM, and SSCRM literature streams based on this study's final dataset. The fact that only 46 papers met the inclusion criteria highlights a striking issue: despite semiconductors' critical role in global supply chains, there remains very limited coverage of SSCM and SCRM in top-ranked journals. Many studies touched on the industry only tangentially, without adequate depth. This paucity of focused research underscores the need for systematic investigations into SSCRM for semiconductors. To our knowledge, this is the first integrative review explicitly examining that intersection.

FINDINGS

The findings are presented in three parts, beginning with insights from the SSCM literature, followed by the SCRM literature, and finally the resulting SSCRM literature. For each stream, we discuss the areas that have been extensively explored as well as the topics that remain under-examined, highlighting opportunities for future research.

SSCM literature

The growing body of research on SSCM in the semiconductor industry has coalesced around three key areas: regulatory compliance, circular economy practices, and geopolitical influences. These interconnected dimensions have shaped both academic discourse and industry practice, reflecting the unique challenges of implementing sustainability initiatives in a highly globalized, technologically complex, and politically sensitive sector. While significant progress has been made in understanding these core areas, several critical gaps remain in the literature, pointing to important directions for future research.

Regulatory Compliance

The semiconductor industry operates under some of the world's most stringent environmental regulations which have significantly shaped SSCM practices. Directives such as the WEEE Recast Directive and REACH have pushed firms to adopt emissions-control systems and restrict hazardous substances in fabrication processes . Compliance efforts often involve balancing environmental performance with operational efficiency, as companies deploy systems to track sustainability metrics and maintain reliable pollution-control mechanisms to avoid fines and supply disruptions (Bellamy et al., 2020). Beyond facility-level operations, these regulations have also driven broader supply chain adjustments to ensure adherence across global supplier networks.

Circular Economy Practices

Circular economy principles have become increasingly important in semiconductor supply chains, particularly in the management of e-waste and resource recovery. Research highlights the adoption of closed-loop systems to recover high-value materials, as well as design-for-recycling strategies that address the large virgin material footprint of semiconductor-based products such as computers and LCD screens (Mazahir et al., 2019). Industry studies also point to the role of legislation, such as the WEEE Recast Directive, in advancing reuse, recycling, and remanufacturing practices. At the operational level, firms are incorporating environmental management systems and disclosure practices to improve transparency in material usage and waste reduction across supply networks (Rauer & Kaufmann, 2015).

Geopolitical Influences

Geopolitical developments have become defining drivers in semiconductor SSCM, as national industrial strategies reshape global supply networks. Policies such as the U.S. CHIPS and Science Act promote domestic production, shift investment flows, and impose restrictions on foreign access to critical components (Luo & Van Assche, 2023). These interventions influence not only the structure of global semiconductor supply chains but also the sustainability considerations tied to production regionalization and resource security. Industry-wide collaboration has also emerged as a response to these pressures, with consortia such as Sematech demonstrating how joint investments can enhance competitiveness, accelerate technology adoption, and strengthen long-term sustainability outcomes (Joglekar et al., 2016; Lo & Zhang, 2024).

Main Findings and Less Explored Areas

Although research has generated insights into compliance, circular practices, and geopolitical drivers of SSCM, several gaps remain. Power dynamics within multi-tiered supply chains are insufficiently understood, particularly how dominant buyers impose sustainability requirements on smaller suppliers with limited resources (Diebel et al., 2024). While semiconductors are both enablers and consumers of digital technologies, there is little research on how AI or blockchain could enhance transparency, predictive monitoring, and sustainability enforcement. Life Cycle Assessment (LCA) approaches are underutilized, leaving unanswered questions about the comparative environmental impact of different semiconductor manufacturing processes and technology nodes. Finally, despite the semiconductor industry's tradition of consortia-based R&D, few studies have examined how collaborative governance models could drive sustainability innovation through pre-competitive collaboration (Joglekar et al., 2016; Lo & Zhang, 2024).

The under-explored aspects of SSCM in the semiconductor industry represent critical research gaps with far-reaching implications. The lack of attention to power dynamics in supply chain tiers is particularly consequential, as the semiconductor industry's concentrated structure creates significant asymmetries where dominant firms impose sustainability requirements on suppliers without addressing capacity constraints or cost burdens. Understanding these dynamics could reveal why sustainability initiatives often fail to penetrate beyond first-tier suppliers, despite the industry's environmental impact being concentrated in upstream material extraction and processing. The absence of research on AI-driven sustainability optimization represents another crucial gap, especially given the dual role of semiconductors in both enabling and consuming these technologies. As the industry faces increasing pressure to reduce its carbon footprint while meeting exponential demand growth, machine learning applications for energy optimization and predictive maintenance could unlock step-change improvements in resource efficiency.

Similarly, the limited application of LCAs is particularly problematic for an industry where different manufacturing nodes (for example, 5nm vs. 28nm) have dramatically different environmental footprints, leaving firms and policymakers without robust data to guide decarbonization strategies. Finally, the lack of research on collaborative governance models represents a missed opportunity for an industry with a strong tradition of consortia-based R&D, where pre-competitive sustainability innovation could yield sector-wide benefits. Addressing these gaps is essential for developing SSCM approaches that match the semiconductor industry's unique technical complexity, geopolitical sensitivities, and environmental challenges.

SCRM Literature

The research on SCRM in the semiconductor industry has developed around three central themes: demand-side risks, supply-side risks, and systemic and relational risks. These streams of inquiry reflect the industry's unique exposure to volatility, long production lead times, and complex interdependencies across global networks. While the literature identifies a wide range of risk factors and mitigation strategies, significant gaps remain in how these risks are understood, measured, and managed.

Demand-Side Risks

Semiconductor supply chains are consistently exposed to volatile demand and market shocks. Research shows that sudden surges or collapses in demand, particularly in automotive and consumer electronics, lead to inventory disruptions and production bottlenecks (Rajavi et al., 2024; Shan et al., 2014). The COVID-19 pandemic and earlier events like the 2011 Japan earthquake revealed how fragile the supply chain becomes when demand exceeds available supply. Firms attempt to buffer these risks through contractual risk-sharing, sourcing diversification, and resilience strategies (Cohen et al., 2022), though the long semiconductor lead times often amplify disruption severity.

Supply-Side Risks

On the supply side, geopolitical interventions, natural disasters, and technological shocks repeatedly destabilize semiconductor production. The 2018 ZTE ban disrupted supplier networks (Dong et al., 2018), while the Tōhoku earthquake halted Texas Instruments' production for months (Jacobs et al., 2022). Studies also highlight yield uncertainty, where defects and process inefficiencies create deviations from planned output, raising costs and delaying delivery (Hwang et al., 2018; Tang et al., 2014; Xiao, 2020). To cope and stabilize firm performance, firms rely on mergers and acquisitions (M&As) such as the ON Semiconductor–Fairchild merger, procurement adjustments, voluntary disclosures, and wholesale price contracts (Gao et al., 2014; Hwang et al., 2018; Tang et al., 2014; Xiao, 2020). Firms also pursue capacity reservations, supply diversification, and flexible sourcing, especially in the automotive sector where electric vehicle (EV) demand has intensified shortages (Clottey & Benton, 2024; M. A. Cohen & Kouvelis, 2021). Vertical acquisitions, such as Western Digital's purchase of Komag, and deals by Texas Instruments and Intel, further buffer against yield and technology risks (Frésard et al., 2020; Wang et al., 2024).

Systemic and Relational Risks

A third stream of research highlights systemic vulnerabilities and relational dynamics within semiconductor supply chains. Multi-tier structures heighten exposure to supplier opportunism and compliance failures, underscoring the importance of relational governance (Yan et al., 2015). Strategic partnerships, such as LG Electronics' ties with TSMC, improve pricing visibility and coordination, while multisourcing strategies, contractual penalties, and performance-based clauses, exemplified by Intel's 15-minute response requirements, help prevent production halts and contain disruption risks (Ang et al., 2017; Kim et al., 2010). The trade-offs between outsourcing and in-house production add further complexity: fabless firms like Marvell outsource heavily, while integrated manufacturers such as Fairchild incur higher capital costs in exchange for stability (Bhaskaran & Ramachandran, 2011; K. Moon & Phillips, 2014; S. K. Moon & Phillips, 2021).

Research also highlights how collaborations within business groups, such as TSMC–UMC, strengthen resilience to external shocks (Mahmood et al., 2013). Critiques of Just-in-Time inventory practices illustrate a shift toward resilience, with Toyota stockpiling semiconductor chips in the wake of shortages (Choi et al., 2023). At the network level, systematic risks faced by firms such as ASE and Sematech demonstrate how supply chain topology affects resilience (Cozzolino & Rothaermel, 2018; Osadchiy et al., 2016; Pathak et al., 2014). Marketing strategies, like DuPont's branding efforts for semiconductor equipment, further stabilize buyer-supplier ties (Dahlquist & Griffith, 2014).

Main Findings and Less Explored Areas

Although the SCRM literature identifies a wide range of risks, several areas remain insufficiently explored, yet highly consequential for semiconductors. Yield uncertainty is frequently acknowledged but underexamined relative to geopolitical or demand risks, despite its direct effect on cost, capacity, and product reliability (Gao et al., 2014; Hwang et al., 2018; Tang & Kouvelis, 2014; Xiao, 2020). Future research could investigate how new analytical and digital tools mitigate yield variability and enhance process predictability, given the increasing reliance on data-driven decision-making in semiconductor operations. Similarly, multi-tier opportunism and compliance risks have received limited empirical scrutiny, even though the industry's reliance on a few specialized suppliers in Southeast Asia disproportionately magnifies these vulnerabilities (Yan et al., 2015; Zhao et al., 2019). Examining governance practices, transparency mechanisms, and sustainability considerations could reshape buyer–supplier power dynamics in these highly concentrated ecosystems. Finally, systematic risks embedded in supply chain topology including interdependencies across fabs, equipment providers, and raw material suppliers are conceptually discussed but rarely quantified in semiconductor contexts (Cozzolino & Rothaermel, 2018; Osadchiy et al., 2016; Pathak et al., 2014). Understanding how network-wide shocks interact with demand volatility, amplification effects, and long production lead times (also known as the bullwhip effect) is therefore a critical but overlooked dimension.

These underexplored areas warrant deeper research given semiconductors' capital intensity, technological precision, and geopolitical centrality. Yield risks are amplified by extreme miniaturization and process complexity, where even marginal deviations can generate billions in losses. Multi-tier opportunism and compliance failures carry disproportionate consequences because a single supplier's non-performance can stall global industries, from automotive to defense (Yan et al., 2015; Zhao et al., 2019). This makes investigating how transparency, alignment, and relational safeguards can strengthen resilience across extended networks, especially relevant. Systematic risks are further compounded by geographical concentration in regions such as Taiwan and South Korea, combined with escalating demand from EV manufacturing firms and AI computing. Future research will need to examine how firms buffer against localized disruptions, combining agility, adaptability, and alignment, to stabilize global supply chains. Addressing these overlooked areas is therefore critical to building resilience in an industry that underpins both economic competitiveness and national security.

SSCRM Literature

The limited scholarship explicitly addressing SSCRM in semiconductors has emphasized three focal areas: resource-intensive manufacturing, and resilience frameworks, and geopolitical dependencies. Together, these themes illustrate how sustainability and risk are intertwined in an industry marked by geographic concentration, scarce input dependencies, and recurring disruptions. While these studies identify important risk drivers, they remain narrowly focused on immediate operational concerns, leaving broader systemic and long-term sustainability dynamics underexplored.

Resource-Intensive Manufacturing

Semiconductor manufacturing is uniquely resource-intensive, requiring vast amounts of ultrapure water, rare earth metals, and energy. Disruptions in inputs such as neon gas, gallium, and copper have halted production lines, demonstrating how operational risks are closely intertwined with sustainability concerns (Jacobs et al., 2022; Khademi & Eksioglu, 2018). Studies emphasize the dual challenge of maintaining resource security while minimizing environmental externalities, as shortages often drive up carbon emissions through emergency logistics and accelerated production restarts. Yet little research links resource dependency with long-term sustainability transitions, such as water stewardship under climate change or material circularity in rare earth supply.

Frameworks for Resilience

A small but growing body of research applies frameworks such as Triple-A and Triple A&R to assess how semiconductor firms can mitigate supply chain vulnerabilities. These frameworks highlight the role of agility and adaptability in responding to short-term shocks, while robustness and resilience address long-term strategic challenges (Cohen & Kouvelis, 2021; Kovács & Falagara Sigala, 2021). Policy interventions, including the U.S. and EU CHIPS Acts, further illustrate how resilience-building efforts are increasingly tied to sustainability objectives, with governments embedding carbon reduction, workforce development, and supply security into semiconductor investment programs (Ravi, 2024). Despite these linkages, current work emphasizes reactive adaptation to disruption rather than proactive integration of sustainability and risk management into unified strategies.

Geopolitical Dependencies

Semiconductor supply chains are acutely vulnerable to geopolitical volatility due to their concentration in East Asia, particularly Taiwan and South Korea. Export bans, trade disputes, and localized natural disasters in these regions have repeatedly triggered cascading disruptions across automotive, healthcare, and consumer electronics industries (Harland, 2021; Lee, 2023). Scholars note that this geographic clustering amplifies systemic fragility, leaving the semiconductor sector more vulnerable than many other industries dependent on geographically diversified production networks. While policy interventions such as the U.S. and EU CHIPS Acts seek to rebalance production geographically, research has yet to assess how such industrial policies interact with sustainability imperatives.

Main Findings and Less Explored Areas

Despite these valuable insights, several critical themes remain underexamined. Power asymmetries across supply tiers influence how sustainability practices diffuse, with upstream suppliers often lacking the capacity to meet standards imposed by dominant buyers (Villena, 2019; Villena & Gioia, 2018). Digital tools such as AI and blockchain, widely cited as potential enablers of predictive risk monitoring and supply chain transparency, remain scarcely applied to semiconductor-specific SSCRM (Bellamy et al., 2020). In addition, long-term climate-related risks, such as water scarcity from droughts and persistent fluorinated gas emissions, are rarely addressed in current scholarship, despite their potential to fundamentally reshape the industry's sustainability profile (Kelion, 2021; Mazahir et al., 2019).

These gaps carry significant consequences for the industry's future. Weak upstream governance mechanisms undermine supply chain-wide compliance and leave sustainability goals unevenly enforced. Underutilization of AI-enabled monitoring forfeits opportunities for real-time disruption prediction and resource optimization. Ignoring climate-related risks renders the sector reactive to chronic environmental pressures rather than proactive in addressing them. Closing these gaps is essential if semiconductor supply chains are to evolve into systems that are not only resilient to acute shocks, but also adaptive to chronic sustainability challenges of the coming decades (Cohen & Kouvelis, 2021; Villena & Dhanorkar, 2020).

DISCUSSION

This discussion links the underexplored themes identified in the SSCM, SCRM, and SSCRM literatures to the established sustainability and risk frameworks of ESG, TBL, Triple-A, and Triple A&R, highlighting how emerging challenges can be reframed as research opportunities (see Table 3). Thus, we outline a forward-looking agenda to guide scholarship on SSCRM in the semiconductor industry.

Research Question 1: How can AI-driven analytics enhance sustainability, transparency, and risk management in semiconductor supply chains?

As discussed previously, AI-driven analytics offer powerful tools for enhancing transparency, forecasting disruptions, and advancing sustainability in semiconductor supply chains. Extant research emphasizes their contribution to resilience through predictive capabilities, demand sensing, and optimization of decision-making processes (Felsberger & Reiner, 2020; Shafiq et al., 2016), yet their integration with sustainability imperatives remains insufficiently examined. This omission is notable given that semiconductor production is simultaneously resource-intensive, demanding extraordinary volumes of ultrapure water, rare earth inputs, and energy, and acutely vulnerable to systemic shocks, including geopolitical disruptions, yield uncertainties, and climate-induced resource scarcities. At the same time, AI has the potential to enable real-time monitoring of environmental impacts, predictive assessment of social risks, and improved governance through enhanced traceability and disclosure mechanisms, thereby addressing both operational volatility and stakeholder accountability. By situating AI not merely as a risk mitigation tool but as a driver of sustainable transformation, future research can illuminate its potential to recalibrate semiconductor supply chains from fragile and resource-intensive systems into more transparent, equitable, and environmentally responsible networks.

We suggest that the ESG framework is particularly relevant here as AI can enhance all three dimensions. On the Environmental side, AI can enable precise tracking of carbon emissions (Olawade et al., 2024), water use, and waste streams, supporting compliance with tightening regulations. On the Social side, it can monitor labor practices across multiple supply tiers, improving visibility into working conditions and supplier inclusion. On the Governance side, AI can support ethical sourcing and disclosure requirements by strengthening traceability and real-time reporting. Future research should investigate how AI-driven traceability and predictive analytics strengthen compliance with ESG goals while mitigating operational risk.

Research Question 2: How do sustainability and risk management practices reshape power asymmetries between buyers and suppliers in semiconductor supply chains?

Semiconductor supply chains are highly asymmetrical, with leverage often concentrated among advanced foundries such as TSMC and Samsung or suppliers of scarce inputs like neon gas, gallium, and rare earth elements (Bastl et al., 2013; Chen & Miller, 2015). Sustainability practices are beginning to reshape these dynamics: upstream suppliers with strong environmental capabilities can gain bargaining power as buyers prioritize sustainable sourcing, while large downstream firms in automotive, defense, and consumer electronics increasingly impose sustainability and risk-management standards across their networks. These opposing pressures make semiconductors a critical context for examining how SSCRM reshapes power relationships across global, multi-tier supply chain networks.

We propose that the TBL framework aligns well here, since power rebalancing hinges on trade-offs between Profit, People, and Planet. For Profit, sustainability requirements increasingly shape contract terms and pricing, with suppliers that demonstrate strong environmental capabilities gaining leverage through preferential contracts or premiums. For People, buyer pressure on labor standards and inclusion often extends beyond first-tier suppliers, yet smaller firms may struggle to comply without additional support, reinforcing power asymmetries. For Planet, environmental obligations such as carbon reduction, water stewardship, and recycling influence procurement choices, giving greener suppliers bargaining advantages. Future research should examine how these sustainability imperatives reshape procurement strategies, supplier leverage, and bargaining outcomes, offering insight into how SSCRM transforms traditional power asymmetries in semiconductor ecosystems.

Research Question 3: In what ways do escalating geopolitical tensions amplify risk and sustainability trade-offs in semiconductor supply chains?

Geopolitical dependencies are one of the most extensively examined themes in semiconductor supply chains, with research highlighting how U.S.–China trade disputes, export bans, and techno-nationalist policies repeatedly destabilize semiconductor supply chain networks

(Fan et al., 2022; Luo & Van Assche, 2023). With production heavily concentrated in East Asia, supply chains remain highly exposed to sanctions, regional conflicts, political rivalries, and industrial policy interventions. While this literature underscores the sector's acute vulnerabilities, several critical questions remain underexplored. Future research should investigate how regional strategies, such as duplicating fabs under the CHIPS Acts, affect energy demand, carbon emissions, and resource efficiency; how techno-nationalist policies reshape labor standards, transparency, and governance practices across supply chain tiers; and how resilience strategies pursued under geopolitical pressure, such as stockpiling and regional buffer capacity, produce unintended environmental externalities.

Triple A&R provides a particularly useful lens here. Robustness captures the extent to which semiconductor firms can create buffer capacity through stockpiling rare inputs or establishing dual-sourcing arrangements to insulate against export bans. Resilience highlights the ability of supply chains to recover rapidly from disruptions such as sanctions, embargoes, or regional conflicts, requiring not only operational redundancies but also adaptive contracting and alternative logistics routes. Realignment emphasizes longer-term structural shifts, such as reconfiguring supply geographies away from overconcentration in East Asia or aligning new regional fabs with sustainability imperatives like renewable energy integration and water recycling. Together, these dimensions clarify how resilience-building interacts with sustainability, underscoring the need for research that quantifies both the benefits and trade-offs of geopolitical realignments in semiconductor supply chains. Future research should systematically examine how resilience strategies adopted under geopolitical pressure can be designed to balance security with sustainability, quantify the environmental and social costs of regionalization, and develop Triple A&R–based models that evaluate when robustness and resilience justify their sustainability trade-offs.

Research Question 4: How can collaborative governance models enable sector-wide sustainability innovation and resilience in semiconductor supply chains?

The semiconductor industry has a well-established tradition of collaboration through consortia such as Sematech, which historically advanced R&D, capacity building, and standard-setting across competing firms. However, this collaborative capacity has rarely been extended to sustainability and risk management, even though evidence shows that sustainability initiatives often stall at first-tier suppliers, where high compliance costs and limited technical capabilities restrict implementation (Rauer & Kaufmann, 2015; Villena, 2019). In a sector that depends on resource-intensive inputs and high-energy manufacturing processes, shared governance structures could help distribute both responsibility and resources across the network. Extending collaborative models, whether in the form of industry consortia, multi-stakeholder alliances, or public–private partnerships, offers the potential to drive pre-competitive sustainability innovation, enable joint investment in cleaner technologies, and establish sector-wide standards that improve both resilience and environmental performance.

Using the ESG framework here, future research should shift from firm-level assessment to understanding how environmental, social, and governance responsibilities can be jointly governed across supply chain networks. This includes studying how firms can jointly facilitate environmental progress through shared carbon-reduction commitments or water-recycling systems, support social responsibility by offering supplier training and labor standards enforcement across multiple tiers, and strengthen governance through collaborative compliance platforms, traceability systems, and shared reporting structures. Future research should also examine how such network-level governance arrangements create incentives for participation, reduce duplication of effort, and enable sustainability innovations to move beyond individual firms and become embedded as industry-wide practices.

RQ5: How does the bullwhip effect influence both operational resilience and sustainability outcomes in semiconductor supply chains?

The bullwhip effect, where small fluctuations in demand magnify into large swings in orders upstream, poses a major challenge for semiconductor supply chains by amplifying inefficiencies, environmental impacts, and operational volatility. Long lead times, capital-intensive processes, and highly specialized inputs exacerbate this dynamic, leading to excess inventory, costly overproduction, and inefficient capacity utilization (Esenduran et al., 2022; Shan et al., 2014). These operational inefficiencies also carry sustainability implications: disproportionate energy and water use, material waste from overproduction, and additional emissions from emergency logistics all undermine environmental objectives. While approaches such as vendor-managed inventory (VMI), advanced forecasting, and Collaborative Planning, Forecasting, and Replenishment (CPFR) have been proposed in the literature, their ability to deliver both operational stability and sustainability remains unclear.

The Triple-A framework provides a strong foundation for addressing this gap. Agility enables firms to adjust quickly to shifting demand signals, Adaptability supports long-term recalibration of forecasting and production systems as markets evolve, and Alignment ensures that incentives and information are shared across supply tiers to prevent amplification. Future research should examine how these capabilities can reduce variability while linking bullwhip mitigation directly to sustainability outcomes, ensuring that demand management strengthens both resilience and environmental performance in semiconductor supply chains (Kovács & Sigala, 2021; Lee & See, 2004).

RQ6: How can the Triple A&R framework be applied to balance resilience and sustainability in semiconductor supply chains?

While the Triple-A framework has been widely applied in supply chain research, its extension into Triple A&R remains relatively less explored, particularly in semiconductor contexts. We therefore include it as an independent research question to emphasize its potential for addressing the industry's dual imperatives of resilience and sustainability. This framework extends traditional resilience research by combining short-term flexibility with long-term structural readiness, offering a more holistic view of supply chain stability under conditions of uncertainty (Cohen & Kouvelis, 2021). For semiconductor firms, the 3Rs of Triple A&R are particularly salient. Robustness highlights proactive measures such as capacity buffers, dual sourcing, and critical material stockpiling to manage sudden disruptions. Resilience emphasizes rapid recovery after systemic shocks, whether from black-swan events, geopolitical sanctions, or pandemics, underscoring the need for adaptive contracting and distributed fab networks. Realignment addresses the long-term evolution of supply chains, including regionalization strategies (e.g., "China + 1") and alignment of new capacity with environmental priorities like renewable energy integration and water stewardship. Together, these dimensions can clarify how firms can prepare not only for acute shocks but also for chronic sustainability pressures such as carbon neutrality mandates and fluorinated gas regulation.

Future research should explore how semiconductor firms operationalize the full suite of A&R principles while balancing trade-offs between resilience, cost efficiency, and sustainability. This includes examining the viability of buffers and stockpiles under shifting ESG regulations, the scalability of circular economy initiatives as part of realignment strategies, and the governance mechanisms needed to ensure that resilience investments also advance environmental and social objectives.

Insert Table 3 Here

CONCLUSION

This study addresses a critical gap in the literature by conducting the first integrative review at the intersection of SSCM and SCRM in the semiconductor industry. By synthesizing insights from 46 relevant papers published between 2010 and 2024 in top journals, it highlights the distinct challenges posed by the semiconductors' complex, resource-intensive, and globally concentrated operations. To advance knowledge in this underexplored domain, we present six research questions that map future directions at the nexus of sustainability and risk, covering themes such as digital technologies, buyer–supplier dynamics, geopolitical pressures, inventory volatility, collaborative governance, and resilience frameworks. Together, these questions offer a structured research agenda to address the paucity of scholarship in this area and to ensure that semiconductor supply chains evolve in ways that promote resilience, sustainability, and competitiveness.

The novelty of this study lies in its explicit focus on bridging sustainability and risk management, which are often examined in parallel but rarely integrated in semiconductor contexts. By connecting the SSCM and SCRM literatures through the lens of SSCRM, this review underscores the value of cross-discipline inquiry. In doing so, it not only synthesizes existing knowledge but also identifies critical blind spots in this niche area of semiconductor supply chains where empirical evidence remains limited. The proposed research questions thus provide a roadmap for scholars and practitioners, outlining how semiconductor firms can balance technological innovation while fostering long-term environmental sustainability, social accountability, and operational resilience.

As with any literature review, this study has several limitations. First, the scope of journals analyzed was restricted to the *UTD24* and *SCM* Journal Lists. While these journals represent high-impact outlets, this restriction may exclude valuable insights from interdisciplinary sources, particularly in fields such as engineering, information systems, or environmental science. Second, our review was limited to publications between 2010 and 2024. This timeframe reflects the recent surge of interest in semiconductor supply chains but inevitably omits earlier contributions that may still hold relevance. Third, our synthesis is based on secondary sources, meaning that the insights generated here depend on the breadth and depth of the available literature. As a result, while the six proposed research questions highlight promising avenues, they require empirical validation and theoretical development through future studies.

Despite these limitations, this study provides a timely and necessary foundation for advancing SSCRM in semiconductor supply chains. By clarifying where scholarship has been concentrated and where it has lagged, we offer both a diagnostic assessment and a forward-looking agenda. As semiconductors continue to underpin digital transformation, renewable energy transitions, and national security imperatives, the stakes for managing their supply chains sustainably and resiliently have never been higher.

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Table 1

Applications of Frameworks in the Semiconductor Context

Framework	Dimension	Semiconductor Application	Key Sources
ESG (SSCM)	Environmental	Renewable energy for fabrications (fabs); water recycling in wafer production	Friede et al. (2015)
	Social	Ethical labor standards in suppliers; STEM diversity programs	Orlitzky et al. (2003)
	Governance	Anti-corruption sourcing policies; conflict mineral reporting	Baldini et al. (2018)
TBL (SSCM)	People	Community skill development near fabs; fair wages in supply chains	Wilhelm et al. (2016)
	Planet	Recycling rare metals; chip lifecycle e-waste programs	Cohen et al. (2022)
	Profit	Energy-efficient manufacturing; ESG-driven investor mandates	Miller (2020)
Triple-A (SCRM)	Agility	AI-based demand forecasting; diversify suppliers under trade risk	Lee (2004)
	Adaptability	Shift to alternative materials (e.g., GaN) during shortages	Kovács & Sigala (2021)
	Alignment	OEM/government collaboration on ESG metrics	Lee (2004)
Triple A&R (SCRM)	Robustness	Dual-sourcing wafers; stockpiling rare gases	Cohen & Kouvelis (2021)
	Resilience	Regional fab networks (EU Chips Act)	Cohen & Kouvelis (2021)
	Realignment	Carbon-neutral chip initiatives (e.g., Apple/Microsoft)	Cohen & Kouvelis (2021)

Table 2

Article Count by Journal for the SSCM, SCRM, and SSCRM literature streams

Journal Name	Frequency		
	SSCM	**SCRM**	**SSCRM**
Production and Operations Management	2	12	1
Journal of Supply Chain Management	1	1	2
Management Science	1	7	-
Journal of International Business Studies	1	-	-
INFORMS Journal on Computing	1	-	-
Journal of Operations Management	2	5	-
Academy of Management Journal	-	-	-
Journal of Business Logistics	-	3	2
Decision Sciences	-	1	-
Journal of Marketing	-	1	-
Strategic Management Journal	-	1	-
Review of Financial Studies	-	1	-
Organization Science	-	1	-
Total	8	33	5

Table 3

List of Research Questions

Broad RQ	Studies informing RQs	Future Research Ideas
RQ1: How can AI-driven analytics enhance sustainability, transparency, and risk management in semiconductor supply chains?	Felsberger & Reiner (2020); Shafiq et al. (2020)	• AI-driven traceability for ESG compliance (carbon, water, labor) • Predictive analytics for disruption forecasting • AI-enabled optimization balancing risk, cost, and sustainability
RQ2: How do sustainability and risk management practices reshape power asymmetries between buyers and suppliers in semiconductor supply chains?	Mukandwal et al. (2020); Bastl et al. (2013); Chen & Miller (2010)	• Shifts in bargaining power under sustainability mandates • Procurement strategies balancing cost vs. sustainability obligations • Supplier leverage through green capabilities
RQ3: In what ways do escalating geopolitical tensions amplify risk and sustainability trade-offs in semiconductor supply chains?	Tang et al. (2014); Lee & Schmidt (2017); Fan et al. (2022); Luo & Assche (2023)	• Trade-offs between regionalization and carbon footprint • Governance and labor implications of techno-nationalist policies • Environmental externalities of resilience strategies (stockpiling, duplication of fabs)
RQ4: How can collaborative governance models enable sector-wide sustainability	Villena (2019); Rauer & Kaufmann (2015); Elkington	• Role of consortia and alliances in advancing sustainability innovation

innovation and resilience in semiconductor supply chains?	(1997); Wilhelm et al. (2016)	• Shared governance for supporting lower-tier suppliers • Establishing sector-wide sustainability standards to align People, Planet, and Profit goals
RQ5: How does the bullwhip effect influence both operational resilience and sustainability outcomes in semiconductor supply chains?	Shan et al. (2014); Esenduran et al. (2021)	• Evaluating bullwhip mitigation tools (VMI, CPFR) for semiconductor contexts • Modeling environmental impacts of demand amplification • Linking agility, adaptability, and alignment to demand variability control
RQ6: How can the Triple A&R framework be applied to balance resilience and sustainability in semiconductor supply chains?	Cohen & Kouvelis (2021)	• Operationalizing robustness and resilience under sustainability mandates • Evaluating cost–resilience trade-offs in buffers, stockpiling, and dual sourcing • Aligning realignment strategies (regional fabs, renewable energy integration, water stewardship) with long-term sustainability goals

APPENDIX

Journal Name	*UTD24 List*	*SCM List*
Academy of Management Journal	✓	—
Academy of Management Review	✓	—
Administrative Science Quarterly	✓	—
Decision Sciences	—	✓
Information Systems Research	✓	—
INFORMS Journal on Computing	✓	—
Journal of Accounting and Economics	✓	—
Journal of Accounting Research	✓	—
Journal of Business Logistics	—	✓
Journal of Consumer Research	✓	—
Journal of Finance	✓	—
Journal of Financial Economics	✓	—
Journal of International Business Studies	✓	—
Journal of Marketing	✓	—
Journal of Marketing Research	✓	—
Journal of Operations Management	✓	✓
Journal of Supply Chain Management	—	✓
Management Science	✓	✓
Manufacturing & Service Operations Management	✓	✓
Marketing Science	✓	—
MIS Quarterly	✓	—
Operations Research	✓	✓
Organization Science	✓	—

Production and Operations Management	✓	✓
Strategic Management Journal	✓	—
The Accounting Review	✓	—
The Review of Financial Studies	✓	—