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INDUSTRY 4.0 AND AGILE SUPPLY CHAINS FOR SUSTAINABLE DEVELOPMENT: ENABLERS, PRACTICES, AND PERFORMANCE

Mohammad Sultan Ahmaad Ansari [1]
Hothefa Shaker Jassim
Mahmoud Abouraia
Fadi Abdelfattah
Shad Ahmad Khan

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A B S T R A C T

There are ample benefits of integrating Industry 4.0 with Agile Supply Chains (AgSC). The arrival of Industry 4.0 and Artificial Intelligence (AI), Big Data Analytics, Internet of Things (IoT), and blockchain provided great prospects for AgSC that played a responsive role in achieving tractability, responsiveness in establishing resilience and sustainability performance. It will promote impending gains including reduced carbon footprint by incorporating sustainable practices such as eco-friendly packaging material, and market positioning. The 4IR with blockchain can support sustainability by identifying areas of inefficiencies and waste. The organization can take initiative to address them through partnerships. Therefore, the integration of Industry 4.0 in AgSC can bring about a range of benefits. The study followed systematic literature review (SLR), developed hypotheses, and hypotheses are validated based on secondary data collected through SLR to evaluate the benefits of sustainability with Industry 4.0 and AgSC. The critical success factors (CSFs) for Industry 4.0 success are big data, IoT, IIoT, AI, machine learning, and cloud computing Sustainability can minimize waste, reduce carbon footprint, and improve operational efficiency with sustainable practices. Findings show that Industry 4.0 integration can lead to sustainability, and it concludes that Industry 4.0 and AgSC are suitable for competitive in changing global scenarios.

1. INTRODUCTION

Incorporation of Industry 4.0 with Agile Supply Chains (AgSC) can provide significant benefits in terms of sustainability, driving competence, improving visibility and traceability. In this globally changing scenario, the organization is striving for balanced economic growth and sustainability with the help of technology. There is anxiety about consumer expectation, quality management, regulatory requirements, supply chain, and sustainable practices. According to (Ganjavi & Fazlollahtabar, 2023), advanced production systems and quality management are complementary for competitive breakthrough. The industry 4.0 would be significant help in providing real-time data sharing and communication among supply chain partners, coordination, collaboration, and sustainable practices

[1] Corresponding author: Mohammad Sultan Ahmaad Ansari
Email: Mohammad.ansari2040@gmail.com

At the same time automation and smart technologies can streamline processes, optimize operations, and improve overall efficiency in supply chains, which can lower energy consumption, emissions, and improve productivity. According to (Peres et al., 2023), technologies such as Blockchain and Internet of the things (IoT) have improved supply chains' sustainability. The industry 4.0 has revolutionized traditional supply chain, by integrating IoT, AI, Big data, blockchain to monitor efficient operation in near real time. AgSC enabled industry 4.0 can better equip to respond with an unstable market dynamic that can help in controlling risks, reducing waste, supporting sustainable practices in a rapidly changing business environment. Partnerships and market positioning are key factors for integration and commissioning industry 4.0 promote utilization of resources, improved innovation, and competitiveness. The partnership with technological firms can facilitate state-of-the-art technologies, where consulting firms can support finding potential pitfall. The academia can support in selecting technologies to align with industry demand and competitive analysis.

Industry 4.0 technologies such as AI, IoT, Augmented reality, Robotics, Analytics, Blockchain, Cybersecurity, 3-D printing, Industrial IoT (IIoT), machine learning, can minimize carbon emissions. The industry 4.0 faces significant challenges from a cyber security perspective Since it is prone to cyber-attack. Data breach and technological manipulation can disrupt operations that can impact company's goodwill. It can be tackled through robust encrypted security systems, with high protection security system, regulatory compliance, training, retraining through abiding to the best practices. According to (Fatimah et al., 2020), IoT is an integrator for sustainable waste treatment in the similar line the real-time data analytics can optimize raw materials, energy, and water resource. The industry 4.0 can support in responding to market demand by laying emphasis on flexibility, collaboration, and resilience. This research paper explores the role of sustainability with industry 4.0and AgSC. The study emphasizes the challenges, opportunities for industry, institution, practitioners, and policymakers for striving sustainable business

1.1 Research Questions (RQ):

According to (Rajput & Singh, 2022), industry 4.0 achieve a circular economy through reverse planning, and IoT sensors for obtaining real-time information. In such cases AgSC can manage unexpected demand, sourcing without any disruption in maintaining inventory threshold, suppliers' performance, and transportation issues. According to (Sherafati et al., 2019), transportation decisions are to minimize cost and environmental harm for improving sustainability in organization. The following research questions (RQ) were raised based on the sourcing requirements to derive benefits of industry 4.0 and AgSC for sustainable practice:

RQ 1. What are the resilient practices of sustainable practices in AgSC?

RQ 2. How can industry 4.0 support and maintain sustainability in AgSC?

RQ 3. What are the critical success factors (CSFs) for achieving sustainability?

The purpose of this research is to consider the above RQs and to find solutions based on the following research objectives set for this research:

1.2 Research Objectives

The best possible attempts are made to evaluate the influence of industry 4.0 in upholding sustainability in AgSC with an aim of optimizing resources, such as water, energy, raw materials, to minimize waste, carbon emission, and reduce carbon footprint. According to (Costa et al., 2023), IoT, cloud computing, and big data are suitable for agricultural industry that can help in reducing carbon footprint. Accordingly, the following research objectives raised.

a. To identify Industry 4.0 technologies that most significantly contribute to sustainability in agile supply chains.
b. To examine how agile supply chain practices (e.g., flexibility, speed, adaptability, integration) amplify or mediate the impact of Industry 4.0 adoption on sustainable performance.
c. To quantify how Industry 4.0 and Agile supply chain improve economic performance (cost, time, efficiency)
d. To measure the effect of Industry 4.0 adoption level on supply chain agility, resilience, and sustainability

After developing RQs and research objectives it is advisable to find research gaps and to that effect the research gaps are analyzed.

1.3 Research Gaps

Researchers advised identifying the research gaps with the aim of finding uncovered areas. Accordingly, researchers to channel their efforts in finding and proposing the solution. There are always opportunities exist in finding the research gap for any future research. Research gaps within sustainability, industry 4.0and AgSC are remarkable, which offers strong ground to examine the benefits of sustainability with industry 4.0in AgSC. It can facilitate real-time data analytics for a responsive and flexible supply chain through AI, machine learning and blockchain. The integration of industry 4.0technology can fulfill demand for sustainable business practices.

Although researchers have put significant work on sustainability, 4IR and AgSC. According to (Machado et al., 2020), there are research gaps and opportunities for developing agenda of industry 4.0. However, there are further investigations needed for practical purposes for sustainable robust framework such as:

a) Tradeoffs between Agile Supply Chain and sustainability outcomes;
b) Operationalizing circular economy with Industry 4.0 in agile settings;

c) Organizational barriers in adopting sustainable Indusry4.0 practices;
d) Combined resilience–sustainability metrics for digital, agile supply chains.

Lack of research on industry 4.0 and AgSC on carbon footprint optimization.
Addressing these gaps are crucial for evaluating industry 4.0and AgSC to sustainability for theoretical and practical purposes. The following Para discusses literature review, methodology, research finding, discussions, and direction for future research.

2 LITERATURE REVIEW

AgSC is situational requirement where supply of raw materials and demand of finished products are irregular due to product life cycles or affected by external volatility. According to (Dahmani et al., 2021), Industry 4.0offers the better and cleaner products by using appropriate processes. An organization can adjust to unpredictable market conditions for gaining competitive advantage by maintaining agile supply chain. Agile initially designed for software development and after observing its adaptability, flexibility, and iterative development processes, found that it can be suitable for marketing or any other projects that forced industry to adapt to agile due to its transforming paradigm. According to (Al Adresi, 2022), lean and agile underpin to gain competitiveness and it helped supply chains to perform in flexible and rapid manner. The Agile became buzzword and remained CSFs for management and implementation of the project. According to (Bai et al., 2022), Industry 4.0having relationships with sustainable development goals (SDGs), CE and its practices can be CSF for industry 4.0 success. Various paradigms of industry 4.0, AgSC and sustainability are correlated with supply chain, which is discussed in detail in the following Para as part of literature review.

2.1 Agile Supply Chain Management

AgSC is in position to meet and exceed customers, suppliers, and producers' expectations in a near real by meeting dynamic demand and supply conditions, controlling cost, time, specification by fulfilling service level agreements (SLAs). According to (Piprani et al., 2024), agile and resilient supply chain mediates relationship for improved performance. There are important aspects of AgSC that support flexibility, innovation, visibility, collaboration, customer service, counter risk, improved service quality, and continuous enhancement. According to (Ansari, 2022), improvement in terms of service quality enhances employee satisfaction and continuous improvements. The AgSC shall be in position to align with supply, distribution, sourcing, and production.
Technologies such as IoT, IIoT, computing can support resource utilization and minimizing waste. It will improve visibility, clarity, resource improvement, and reduce carbon footprint. According to (Hettiarachchi et al., 2022), Industry 4.0, CE, AgSC and IoT are the most researched technologies. It facilitates the real time visibility of inventory, work in progress, transportation status, and in process order. According to (Sharma et al., 2024), Industry 4.0 practices create smart, sustainable, agile, and resilient supply chains for sustainable business value. It is doable through collaboration with suppliers and distributors through coordination and information sharing for faster responses.
The goodwill approach strives to fulfill just in time products inventory requirements in maintaining SLAs to cover customers and suppliers' risk. According to (Sarkar et al., 2023), Poor infrastructure, non-supportive policy ecosystem and changing behavior are barriers to major risks. Proactively recognizing and mitigating risks can disrupt overall sourcing, such as geopolitical events, natural disasters, or supplier failures. It will revive and optimize supply chain processes to enhance agility and efficiency over time. According to (Ansari, 2022), AgSC is in position to provide remarkable advantages in deliverables, waste saving, and improved operational efficiency.

2.2 Sustainability and Industry 4.0

Industry 4.0 has made a remarkable change in basic assumptions for being intelligent, smarter, effective, efficient, and interconnected industrial processes. According to (Al Halbusi et al., 2024), the fear of failure among entrepreneurs negatively influenced that can overcome through strategic planning, taking care of productivity measures and managing operational excellence. The increase in productivity, optimizing resource utilization, and improving quality can provide an opportunity for entrepreneurs. According to (Díaz-Chao et al., 2021), a business model can generate significant effects on profitability due to use of industry 4.0. However, technologies and human capital contribute considerably. According to (Pandey et al., 2024), digitalization of the supply chain and data security are the most prominent enablers of industry 4.0. In this case embracing industry 4.0 tools enable enterprises to stay effective, innovate faster by evolving customers' demand in a rapidly changing global market.
Industry 4.0 includes multiple technologies such as AI, machine learning, Big Data, automation, IoT, Analytics, Robotics, 3D printing, cloud computing, augmented reality, and cyber security that have made changes in the basic assumptions and functioning of system. According to (Pachouri et al., 2024), big data analytics, AI, augmented reality, and virtual reality supported the environment. Analytics helps in evaluating quantum data generated through IoT to gain insights, predict trends, which supports data-driven decisions. AI algorithms and machine learning can analyze, automate, predict failure, and support in optimizing manufacturing activities by developing autonomous systems. According to (Gu et al., 2019), Industry 4.0 architecture can achieve effective product modularization and prominent level of information availability.
The industry 4.0 facilitates quantum data storage in a safe environment through remote access by deploying distinct types of software such as software-as-a-service, Infrastructure as a service (IaaS), Platform as a service and its multiple applications in manufacturing environments. The services face challenges in maintaining security due to increased connectivity, large flow, and exchange of data though different nodes. According to (Silva & Sehnem, 2022), Industry 4.0 is

supporting in implementation of circular economy, digitization, digital solutions, and shared platforms. Whereas augmented reality and virtual reality used for training and development of workers' skills, industrial settings, troubleshooting for reduce downtime.

Sustainability involves three critical areas, economy, social, and environment. According to (Mwenda et al., 2023), sustainable environment practices support supplier relationship, customer relationship, and lean supply chain practices for significant effect on financial sustainability. This means that sustainability needs to fulfill current generations' needs without conceding future generations' requirements. It must evaluate reducing environmental impacts on depleting natural resources, retain and maintain natural resources for future through conservation of reserves and by use of renewable energy. According to (Abdelfattah et al., 2025), firms should focus on green product innovation and develop while policymakers should foster trust and satisfaction through transparent and supportive policies to encourage green investments. (Abdelfattah et al., 2025). At the same time, the efforts on reducing emissions to contain pollution, minimizing waste to protect environment, ecosystem and maintain ecological balance. According to (Hughes et al., 2022, the roadmap towards industry 4.0 is effective and suitable for sustainability goals.

It is need of the hour to promote and practice social justice, social equity by respecting, upholding human values and human rights through ensuring quality of work life, fair wages, and honoring promises of labor rights, which is bare minimal contentment of social justice. According to (Yadav et al., 2020), organizational and economic challenges emerge as the most critical aspect of social justice by maintaining economic sustainability and profit generation without damaging depleting natural resources. It is essential to invest in research for sustainable future through developing innovative products and services. According to (Palsodkar et al., 2024), multi-skilled employees have better prospects of developing innovative and sustainable products.

2.3 Supplier Sustainability for Agile Supply Chain

Suppliers' sustainability measures capability to align with organization's goals, rapid response, competent resource allocation, adaptive capacity, redundancy, diversification, and flexibility. According to (Ghobakhloo & Fathi, 2021), Industry 4.0 enhances capacity and reintroduces eco-friendly products economically and competitively. Where suppliers should be in position to respond quickly to disruptions or predefined responses to minimize downtime in case of operational disruptions. It is essential to conduct the reallocation of stock, altering generation plans, and conveying assets in fulfilling SLA.

AgSC can work as an alternative route for suppliers or coordinator to ensure continuity in supply and delivery despite disruptions in primary channels. AgSC is in position to implement temporary solutions or workarounds during disruption in building redundancy in sourcing, routes, planning, process, production and to mitigate risks for better productivity. According to (Dev et al., 2021), Industry 4.0 capabilities, paying attention in production and productivity management system. AgSC is flexible and compliant with changing production requirements that should quickly adjust to customers' demand, in which risks identification and impacts assessed. It is necessary to develop a strong relationship with customers, suppliers, partners with mutual support and transparent communication for improved agility and enhanced visibility across the value chain. According to (Yilmaz et al., 2022), Industry 4.0 focuses on environmental, social, and operational perspectives. Agility is not only recovering quickly but also learning from disruptions to improve future preparedness, post-disruption reviews, and continuous improvement initiatives to strengthen resilience over time.

2.4 Practical examples of Sustainability with Industry 4.0 and Agile Supply Chains

Following table 1shows practical examples, which demonstrate how Sustainability, Industry 4.0, and Agile Supply Chains intersect in real-world contexts — across manufacturing, organization, and service sectors.

Table 1. Example

Example	Industry 4.0 Technology	Sustainability Outcome	Agility Feature
Siemens	IoT, AI, robotics	Energy & waste reduction	Flexible production
BMW	Blockchain, AI	Circular materials	Supplier responsiveness
DHL	IoT, AI routing	CO_2 reduction	Real-time rerouting
GE Aviation	3D Printing	Less waste & transport	On-demand manufacturing
Ørsted	Digital twin, AI	Renewable optimization	Predictive response
Unilever	Cloud, AI	Less waste	Rapid supplier coordination
P&G	IoT, analytics	Demand matching	Adaptive scheduling

3 METHODS

This research employed a systematic literature review (SLR) methodology to analyze peer-reviewed articles indexed in SCOPUS by following PRISMA principle based on (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), while maintaining transparency and visibility. ("Innovation, and green entrepreneurship are catalysts for sustainability ...") Data collected from SCOPUS indexed journal, which screened and validated for reliability. Scopus databased systematically analyzing sustainability, industry 4.0 and AgSC with an aim of understanding and setting up research models and testing hypotheses. Defining RQs, research gaps, research scopes, and objectives by finding

out latest trend in literature. And how industry 4.0, AgSC can collaborate for sustainability through various permutations and combinations of words such as sustainability, industry 4.0, AgSC, digital transformation, sustainable development, and sustainability. Initially, eight hundred Sixty-four articles retrieved using the keywords in the field (Title-Abstract-keywords). Searches for ('Sustainability") AND ("Industry 4.0" OR "Agile Supply Chain" OR "Carbon Footprint"), Sustainability OR Industry 4.0), AND (Agile Supply Chains OR Sustainability), AND (Global warming OR temperature rise) AND (carbon footprint OR Industry 4.0). The article shortlisting processes are illustrated in Figure 1.

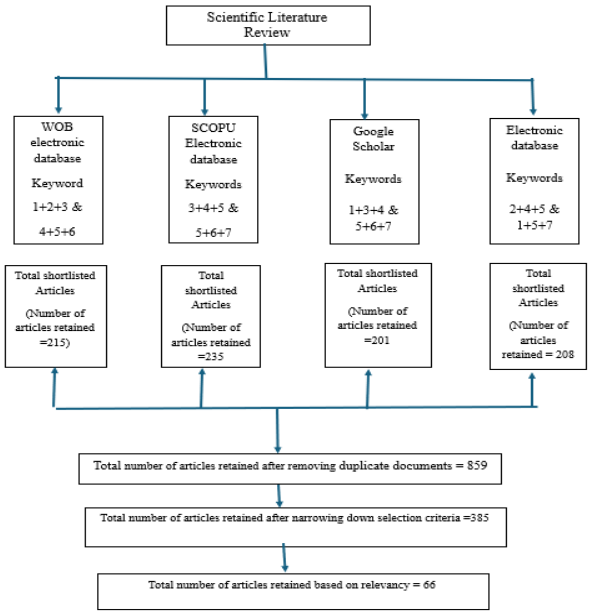

Figure 1. Shortlisting Criteria

The search limited to business and economics, articles of English language only, with key words of sustainable development, carbon footprint, sustainability, industry 4.0, and agile manufacturing system.

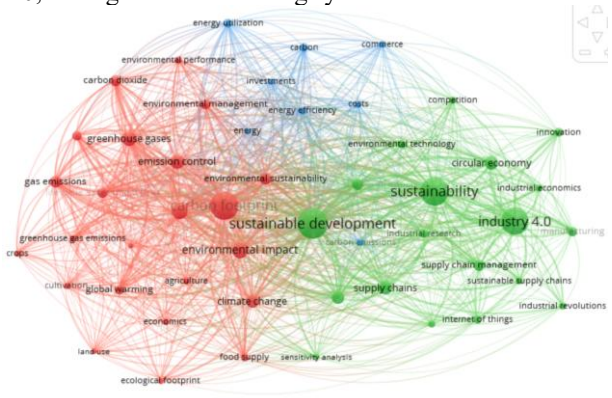

Figure 2. Keywords co-occurrence analysis.
Source: Authors' compilation of Scopus database

The exclusion of non-English publications was due to the language barrier, translation, time, resources, and literature accessibility constrain. There was lack of non-English language proficiency, interpretation, which might lead to shaded concepts.

Further 175 articles are shortlisted based on abstract content, and relevancy and finally Sixty-six articles chosen for this research. Similar bibliometric research analysis retrieved 295 articles and finally selected fifty-seven articles (Tiwari, 2023) was selected for studies. Figures 2, Figure 3, Figure 4 shows keywords co-occurrence analysis, documents by authors and respectively. Figure 4 explicitly shows that the research on sustainability, industry 4.0 and AgSC came up during the last decades, and research published during the last Five years took a quantum jump. The selected articles are from 2019 to 2024, which have a minimum of fifteen citations or above, which are widely read and referred. Hence data synthesis and assessment were done based on the trends, selected studies, barriers, and challenges in integration of industry 4.0 elements.

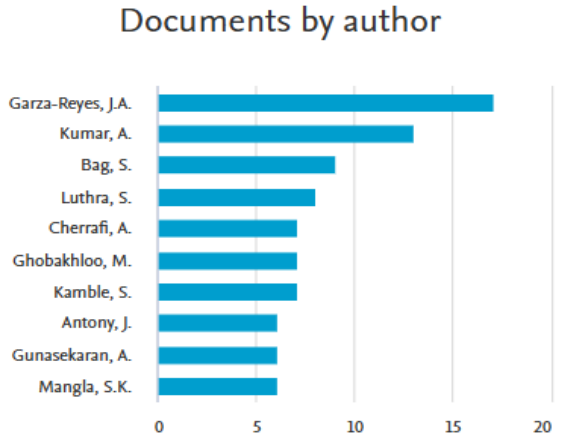

Figure 3. Documents by Author
Source: Authors' compilation of Scopus database

Figure 2 shows keyword co-occurrence analysis, which is a bibliometric technique of research finding used to evaluate the keywords that appear in articles, academic literature, or reports. It supports thematic research area to understand research trends, relationship between the concepts, and emerging topics.

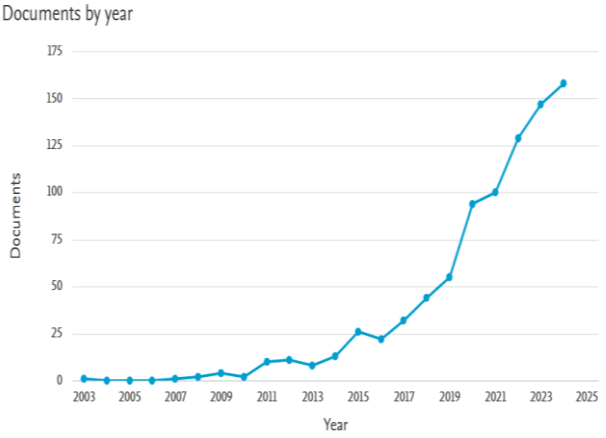

Figure 4. Documents by Year

In this research the keywords "Sustainability," "Industry 4.0" and "Agile Supply Chains" analyzed. Extracted publication was from SCOPUS database that shows co-occurrence of the words.
Source: Authors' compilation of Scopus database
Figure 3 shows articles published by top authors in SCOPUS database. The figure considered the maximum of seventeen articles and minimum of seven articles.
Figure 4. shows the number of articles published in different years on related topics such as sustainability, industry 4.0 and AgSC. from 2003 till 2025. There is a steep rise in the number of published articles from 2022 till date.

4 RESEARCH METHODOLOGY

This research evaluates the impact of industry 4.0, AgSC on sustainability. The topic was shortlisted by literature review, research gaps, and benefits of sustainability on the ecosystem. It not only supports green environment, but also it impacts company performance. According to (Luan et al., 2025), green innovation and green taxation impact environmental sustainability in developing countries. It enhances operational efficiency, service quality, and company bottom line. According to (Horváthová et al., 2019), Industry 4.0 increases efficiency and cost savings. The proposed model deals with industry 4.0 enabled AgSC for optimization of inventory, operational cost, transportational cost, resources usage, waste reduction, carbon footprint, risk avoidance, flexibility, adaptability, and profitability. It develops a framework with the aim of finding the impending benefits of sustainable practices and how it can support business and environmental sustainability. The proposed model is depicted in Figure 5.

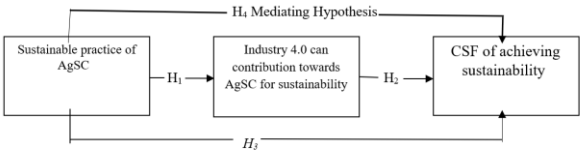

Figure 5. Research Model

The following hypotheses developed for assessing the proposed Model:

H_1 – Sustainable practices will have a positive and lasting impact on industry 4.0.

H_2 – AgSC will support in achieving sustainability.

H_3 –AgSC sustainable practices will support in achieving CSF of sustainability.

H_4 – Sustainable practices will integrate industry 4.0 for sustainability.

6 HYPOTHESES DISCUSSIONS

It is important to frame the hypotheses to find the mediation role of sustainable practices in forming the relationship among sustainability, industry 4.0 and AgSC. Following Para discusses hypotheses of this research.

H_1 – Sustainable practices will have a positive and lasting impact on industry 4.0.

Industry 4.0 technologies have a positive effect on achieving CSFs for sustainability. According to (Sony & Naik, 2020), industry 4.0 can link with socio-technical systems, infrastructure, technology, processes, culture, and achieving sustainability. The factors may vary depending on types of industry. However, CSFs for sustainability are project control, leadership commitment, stakeholder engagement, management of resources, risk management, long term goal, and corporate social responsibility. According to (Felsberger et al., 2022), sustainability can be improved through the dynamic capabilities of industry 4.0 by exploring economic, environmental, and social aspects.
The leadership must set the vision and mission in line with organization's goal and distinctly communicate the strategy for achievement of organizational goal. According to (Kunjumuhammed & Latheef, 2025) sustainable leadership plays a vital role in operations and environmental impact. The most important stakeholders such as employee's engagement are paramount to buy-in of leadership goal. According to (Bhatia & Kumar, 2022), environmental commitment mediates the effect of stakeholder and competitive pressures on industry 4.0. Efficient use of energy, water management, and waste recycling are essential for environmental sustainability. On the other hand, CSR, ethical practices, community engagement, and development remain essential parts of sustainability. Sustainable practices can create positive bearing on industry 4.0 to develop mutual and positive collaboration with technology, and environmental.
The industry 4.0 technologies such AI, IoT, robotics, big data, and real time computing in manufacturing can support accepting sustainable practices. According to (Kamble & Gunasekaran, 2023), industry 4.0 supports circular economy which can help in minimizing waste, improving production processes by maximizing resource utilization. Further, it will minimize operating costs, carbon footprint, reusing, repairing, and refurbishing of products. According to (Contini et al., 2023), the integration of sustainability and digitization is crucial for achieving sustainable production.
The recycling process supported by AI can enhance efficiency by ensuring maximum possible recovered material. AI supported with blockchain can reduce system breakdown, which can help to design products with simpler recycling methods. According to (Gupta et al., 2023), circular economy practices are most important for increasing sustainability performance. Hence it is suggested that sustainable practices minimize costs, recovery, and resilience overall economy. ***Accordingly,***

it is stated that sustainable practices will have a positive and lasting effect on industry 4.0.

H_2 - Agile supply chain will support in achieving sustainability.

AgSC is an amazing enabler of sustainability that supports environmental protection, achieving social and economic goals successfully. It is need of the hour to respond to the change in demand, manage production variations, avoid over production, and curtail waste. It facilitates companies to produce depend on forecast and conserving resources in terms of raw material, capital, energy, man, and machine hour. According to (Gupta et al., 2021), circular economy practices are important for increasing sustainability performance in manufacturing. It focuses on efficiency rather than producing and storing, which results in reducing inventory, waste and reduced environmental footprint.

AgSC follows the lean principles that emphasize elimination of waste, materials, time, energy and procure local sourced raw materials. Locally procured material promotes national economy and fulfills organizational goal of localization. Causal relationships between select enablers lead to circular economy and sustainability (Khanzode et al., 2023). AgSC supports near real-time information in planning value chain stream by optimizing transportation route to reduced carbon footprint. It will reduce lead time, minimize transportation cost, reduce emissions, pollution, and improved air quality. According to (Ahmed et al, 2024), the use of electric vehicles can improve air quality, boost urban living conditions, and relieve noise and air pollution.

AgSC promotes recycling, reused material to conserve resources and disposing of scrap in an environmentally cohesive background to protect environment. According to (Siltori et al., 2021) integration of all value chain activities develops better environmental, social, and economic impacts. It supports circular economy where products utilized for longer intervals of time and scraps used and re-used as long as feasible. An essential trait of AgSC is extensive collaboration with customers, suppliers, and stakeholders. According to (Sharma et al., 2021), the implication of industry 4.0 needs to develop ethical code and standards between stakeholders in multi-tier manufacturing supply chain. It will allow organizations to implement novel solutions rapidly, risk mitigation and adapt to changing regulations and conformity with regulatory body.

AgSC can meet and exceed customer satisfaction, response to customers complaints promptly by engaging customers, which can create customers loyalty, brand loyalty, repurchase behaviour, increased revenue, and profitability. According to (Fallahpour et al., 2021), it is capable to recognize the important evaluation criteria for repurchase and loyalty program. The AgSC with support industry 4.0 in fulfilling consumers expectation of having sustainable products for achieving sustainability. ***Accordingly, it was posited that AgSC will support in achieving sustainability.***

H_3 –AgSC sustainable practices will support in achieving CSF of sustainability.

AgSC has adaptable characteristics that can adjust with the changing circumstances. It can respond rapidly to the operational schedule, improving efficiency for achieving CSFs. The industry 4.0 success depends on CSF for improvement in efficiency, agility, and sustainability. The CSF aligns with the strategic organizational goals, employees' skills, infrastructure readiness, technical maturity, stakeholder collaboration, cyber security, regulatory compliance, and performance management. It can be achieved through a wholistic approach to human factors, technological support for better utilization.

It can realize operational requirements by providing material Just-in-time. It can promote minimal inventory by optimizing available resources by improving workflow for sustainable production. According to (Alkaraan et al., 2023; Alkaraan et al., 2024), practices of production planning and knowledge-collaboration capabilities, are corporate governance mechanisms. AgSC promotes optimized conveyance routes to minimized transportation costs, reduces lead time, and encourages locally sourced materials. It will minimize environmental impact, minimizing carbon footprint through strong relationships and collaboration with suppliers.

CSF is paramount for an organization for achieving its objectives. The CSFs emphasis on achieving customers expectation, customer loyalty, improved productivity for accomplishing everlasting sustainability. According to (Kaswan et al., 2023), integrated application of tools and techniques will enhance productivity and sustainability. The coordinated works will support reducing costs, which makes organizations lean and mean in terms of workforce, material waste, power savings, higher productivity, reduced carbon footprint that effectively minimizes cost and saving for the organization.

As mentioned by (Kumar et al., 2024), lean manufacturing and industry 4.0 promotes cost saving for organizations and promotes higher operational efficiency. The saving can be channeled in improving sustainable practices According to (Khan et al., 2023), industry 4.0 supports in innovation, process, product, business model, and supply chain. It interconnects with product design and development, which facilitate production to launch sustainable products in changing market scenarios. It allows customization of products, production on demand, and delivery of products based on consumption patterns. According to (Zhang et al., 2023), supply chain agility can be boosted through bottom-up approach of smart waste management by utilizing industry 4.0 and circular economy. Hence, AgSC supports in improving carbon footprint, productivity, efficiency, compliance, promoting innovation, shareholder engagement. ***Accordingly, it posited that AgSC will support in achieving CSF of sustainability.***

H_4 – Sustainable practices will integrate industry 4.0 for sustainability.

Sustainable practices work as an intermediary between industry 4.0 and CSF, in which industry 4.0provides technologies, tools, techniques, processes, whereas CSF gives guidelines for achieving sustainability. According to (Kumar et al., 2023), the CSC integrated with industry 4.0 can achieve sustainability in supply chain operations. Technology such as AI, blockchain, IoT, big data, data analytics and real time monitoring can optimize transportation routing that can enhance production efficiency and improve value chain. According to (El Baz et al., 2022), industry 4.0 deployment improves sustainability that influencing integrative readiness. Hence, organizations should use it efficiently and effectively for reducing environmental impact by making use of technologies and realization of CSF for sustainable objectives. According to (Abdul-Hamid et al., 2022), industry 4.0, circular economy, and sustainability practices will lead to sustainability performance.

The industry 4.0 and AI driven tools, blockchain technologies can provide techniques, resources, processes for achieving sustainability. According to (Khan et al., 2021), block chain Technology can significantly improve circular economy practice for improving firms' environmental performance that can stimulate financial performance. It can provide a turning point and strategic advantage for supporting CSFs for maintaining regulatory, ethical, and legal fulfillments. According to (Ferreira et al., 2023), digital technologies, such as AI, Cloud Computing, Robotics, Big Data Analytics, and Blockchain supporting AgSC. Technology such as AI, 3D printing, digital twins can monitor, analyze, and optimize the process without filed trail. According to (Li et al., 2020), digital supply chain platforms mediate the effects of digital technologies on both economic and environmental performance.

The industry 4.0 can evaluate the inefficiencies, optimize resources, minimize carbon emissions, and carbon footprint through use of technology such as AI, IoT, automation, and blockchain. It will optimize resources utilization, minimize energy consumption, and minimize waste for sustainable production. Industry promotes smart energy utilization, innovative practices to support the large-scale industry and provide backing to small and medium enterprises (Pandya & Kumar, 2023). Technology such as 3D printing, and AI supported innovation such as natural language processing, machine learning can provide learning, and support to understand human language. According to (Shahbakhsh et al., 2022), Industry 4.0 has been challenged for its deficit role on human and intelligence. Industry 4.0 having multifunction, such as robot to robotic guidance for interaction of man to machine and vice-versa. According to (Sindhwani et al., 2022), Industry 5.0 is enablers for achieving sustainability by integrating human values with technology. Hence, technologies support sustainable practices. ***Accordingly, it is posited that sustainable practices would integrate industry with 4.0 for sustainability.***

7 FINDINGS

The research evaluated RQs, research objectives, research gaps, research model, hypotheses developed and same are discussed. The following are the potential findings that have emerged, which show that industry 4.0, CSFs and sustainable practices can support AgSC. According to (Ali & Johl, 2023), industry 4.0 readiness has a positive effect on circular economy and sustainable manufacturing practices. Hence industry 4.0 supported by AgSC, can be advantageous for sustainability. Hence the following are the main findings of the study:

a. Technology such as big data, IoT, IIoT, AI, machine learning, cloud computing, analysis, having substantial bearing on CSFs such as company strategy, operational efficiency, financial performance, and sustainability. According to (Mastos et al., 2020), the impact of an IoT solution on sustainable supply chain management is remarkable. It can enhance resources utilization, revolutionary innovation, and curtail risk management.
b. Technologies can enhance operational efficiency, minimize waste, reduce carbon footprint, manage resources that can support sustainable practices. It can optimize cost through integrated production of small batch size. According to (Kamble et al., 2020), industry 4.0 is an enabler of lean manufacturing practices and sustainable organizational performance.
c. The industry, 4.0 AgSC, CSFs can bridge silos in achieving sustainability, operational efficiency through utilizing unified sourcing, energy management practices for reduced carbon footprint. The Potential benefits of AgSC in reducing environmental, social, and economic pressures and contributing to sustainable development (Mwenda et al., 2023).
d. AI, IoT IIoT, and AI, combined with energy-efficient practices, will have an impact on resource efficiency. According to (Lahane et al., 2023), industry 4.0 and blockchain can be enabled for supply chain transparency.
e. Organizations having sustainability principles will perform better and outperform competitors. However, keen attention to be paid for any barriers for improving resource efficiency and sustainability (Rajput & Singh, 2019).
f. The reduction of waste, smaller carbon emissions, and circular economy will improve efficiency.
g. Constructive collaboration with sustainable practices, such as industry 4.0 and CSF will be enabler of sustainability.

The proposed model supports industry 4.0 and AgSC that has bearing on sustainability. Technology improves efficiency, reduces costs, manage risk, minimizes carbon footprint, and customers' retention.

8 CONCLUSION, AND RECOMMENDATION

The amalgamation of sustainability, industry 4.0 and AgSC forms a transformational combination of twenty-first century business practices. It is supported with AI, IoT, block chain and big data analytics to accomplish near-time results with reduced waste, optimizing resources for achieving sustainability. AgSC stresses collaboration, flexibility to meet market demands, where combining industry 4.0 and AgSC forms a cohesive combination with global supply chain goals. The implementation and inclusion of industry 4.0 is essential for achieving sustainability in product and service industries. It will improve operational efficiency, customer engagement, and competitiveness. Findings suggest that industry 4.0, CSFs and sustainable practices are order of the day (Ding et al., 2023). The amalgamated approach aligns with technologies, CSF and drives significant improvement toward achieving a sustainable future.

The research findings emphasize that there is need for comprehensive approach to integrating industry 4.0, CSF for achieving widespread sustainability (Ghobakhloo et al., 2021). Industry needs to take initiative in fast changing paradigm where external environment is not within its control and limited control of interval environment. According to (Piccarozzi et al., 2022), industry 4.0 could be boom for primarily achieving environmental control and triumph for achieving business goals. Technology has played a significant role and is likely to counter challenges such as cybersecurity, autonomous robots, and additive manufacturing, where industry 4.0 could be a great support for society. However, effective implementation of strategy is needed to align with organization culture, stakeholder cooperation, and sustainability goals. In nutshell, incorporation industry 4.0, and AgSC needed for achieving sustainability. Hence, corporations proactively accept performance improvement in active global scenarios.

9 DIRECTION FOR FUTURE RESEARCH

Future research can be taken up on empirical validation It may concentrate on longitudinal studies to detect and examine the changes happening over time. It can be on specific sector for measuring specific results. These insights will channel organizations' sustainable practices and measure the effect of integration in achieving long-term success (Grybauskas et al, 2022). The researcher can empirically examine the conceptual framework presented through primary surveys. It should be in line with industry 4.0, AgSC and sustainability with evidence-based practices. According to (Singh et al, 2025), business performance in relation to ESG disclosures, there is a wide scope of research on the countries like Oman,

10 RESEARCH IMPLICATIONS FOR INDUSTRY, PRACTITIONERS AND MANAGERS

The findings suggest that future studies on empirical validation can help in finding the relationship between industry 4.0, CSFs, and sustainability. The research has great implications for industry with the aim of investment in technology and evaluating feasibility such as payback period and return on investment, market, and technical feasibility. Organizations need to decide how and when to install test and commission industry 4.0 technologies with the aim of attaining sustainability. Investment in technologies shall be in line with organization strategic goals, external environment, competition, and capital expenditure.

Practitioners need to work out the use of technology for higher productivity, optimizing cost, and reduced carbon footprint for holistically achieving sustainability. There are "5 Ps" of the UN Sustainable Development Goals (UN-SDG) i.e., People, Planet, Prosperity, Peace, and Partnerships (5Ps). Practitioners strive to comply with UN-SDG for sustainability by following the law of the land, meeting regulatory directives and compliances.

Managers can initiate policies, procedures, and practices for improvements for adjusting sustainable goals. At the same time, it is essential to develop employees' skills continuously through training and the development of the latest technologies. Technology can help managers achieve higher order production and improve operational efficiency. It will help the manager to plan short and long-term strategies for achieving business goals. The roadmap for absorption of AI, IoT, IIoT, and data science for sustainability. Managers can use technology to monitor raw material and machine utilization for effective utilization of resources.

Declaration of Competing Interest

Impending benefits of sustainability with industry 4.0 and AgSC have no conflicts of interest.

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Data availability

Data used reflected in this research.'

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Mohammad Sultan Ahmad Ansari
Modern College of Business and Science, Oman
Mohammad.ansari2040@gmail.com
ORCID: 0000-0001-7064-3245

Hothefa Shaker Jassim
Modern College of Business and Science, Oman
hothefa.shaker@mcbs.edu.om
ORCID: 0000-0003-2394-1375

Mahmoud Abouraia
Modern College of Business and Science, Oman
Mahmoud.Abouraia@mcbs.edu.om
ORCID: 0009-0008-7104-0989

Fadi Abdelfattah
Modern College of Business and Science, Oman.
Fadi.Abdelfattah@mcbs.edu.om
ORCID: 0000-0002-4665-4777

Shad Ahmad Khan
American University of Phnom Penh Phnom Penh, Cambodia
khan.shadahmad@gmail.com
ORCID: 0000-0001-7593-3487