An Evaluation of Industry 4.0 Capabilities for Sustainable Innovation in Food Sector

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Abstract: - The term "Industry 4.0" refers to a paradigm shift in technology and manufacturing. Using cutting-edge technologies like automation, big data analytics, loT, additive manufacturing, cyber physical system this study investigates relationship between 14.0 and sustainability in food sector. The study's objective is to investigate the key advantages on adoption of 14.0 technologies in food industry, with a focus on environmental impact, waste reduction, and resource efficiency. A review of economic, environmental, and social aspects enables the assessment of prospects and obstacles related to sustainable innovation. Important conclusions highlight how crucial it is for technologies like blockchain and loT to improve food supply chains' waste reduction, transparency, and traceability. The research sheds light on the underutilised 14.0 tools in the current food industry landscape by classifying and highlighting their significance. Research highlights the potential of 14.0 to promote environmentally friendly business models, improve operational effectiveness, and support more general sustainability objectives, such as development of innovative green processes. The primary themes centre on how 14.0 models incorporate technology breakthroughs while paying particular attention to sustainability principles. The study also discusses execution barriers, specifically regarding tracking and monitoring products for quality assurance. The consequences for society and economy highlights the 14.O's transformative potential in building a robust and sustainable future for global industries.

Key-Words: - Industry 4.0, Sustainability, Food Sector, Sustainable Innovation, Technology, Innovation

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1 Introduction

Industry 4.0 (I4.0), referred to as the Fourth Industrial Revolution, represents a significant and transformative shift in industries of manufacturing and technology, with wide-ranging implications on a global scale. The process encompasses incorporation of advanced technologies, including Internet of Things (loT), artificial intelligence (Al), big data analytics, and automation. These technologies possess capability to significantly change business operations and support innovation. The food industry is significantly influenced by development of I4.0, as it offers a chance to reconsider conventional methods in accordance with objectives related to sustainability and innovation. The evaluation of implementation of I4.0 has been extensively conducted in various sectors such as automotive, aeronautical, and railway. This evaluation has shed light on emergence of advanced technologies and applications that significantly improve operational efficiency and enhance competitiveness as mentioned in [1]. Furthermore, there is an increasing acknowledgment of necessity to incorporate resilience and adaptability into value chains, with Industry 4.0 assuming a crucial function in attaining these goals [2]. This encompasses not only smart manufacturing, but also extends to areas such as smart products and services, smart supply chains, and smart working practises. The expanding scope of Industry 4.0 offers new possibilities for innovation and generation of value [3]. Furthermore, there is a growing recognition of integration between Industry 4.0 and sustainability, which holds promise of transforming global production systems and encouraging a more sustainable and resilient future for industries on a global scale [4]. The current research problem refers to the integration of I4.0 capabilities into sustainable innovation within food industry. The potential transforming effects of I4.0 technologies on various sectors have been widely acknowledged, however, their specific application and impact on sustainable practises within food industry have not been fully explored. The evaluation of utilisation of I4.0 capabilities in food sector to encourage sustainable innovation is of utmost importance, considering various factors including resource efficiency, waste reduction, and ethical sourcing. Understanding this integration is of utmost importance given essential function of food industry in tackling global sustainability challenges. To begin with, the issue of resource depletion is of great significance, as agricultural sector's significant demand for water, farmland, and energy produces significant pressure on ecosystems. The industry plays a significant role in decline of environment, as it releases considerable amounts of greenhouse gases, with livestock farming and transportation being particularly prominent contributors. Additionally, practises such as deforestation, pesticide use, and intensive farming contribute to these issues with environment. Food waste is a global problem that affects entire supply chain, resulting in inefficient use of resources, a decline in food insecurity, and contributing to emission of greenhouse gases in landfills. Finally, the issue of energy inefficiency poses significant challenges from both environmental and economic perspectives [5-7].

1.1 Interrelationship between Food Industry and Sustainable Innovation

The food industry is undergoing notable transformations because of crucial for sustainable innovation and integration of I4.0 technologies. The technologies encompassing Internet of things (loT), automation and big data management, enable digitization of manufacturing environment. These technologies also facilitate data-driven decision-making by optimising processes. The integration of I4.0 technologies, including big data management, loT and automation leads to a significant revolution in operational processes of companies operating in food industry [7].

Figure 1. Sustainable Food Systems Overview [8]

This process of transformation subsequently gives rise to development of supply chains that are more agile and responsive, exhibiting dynamic and collaborative characteristics. The implementation of I4.0 technologies in food industry facilitates establishment of supply chains that exhibit exceptional adaptability [9]. The dynamic supply chains in question engage in continuous gathering and analysis of data from multiple locations within supply chain, encompassing production, transportation, and consumer behaviour.

Collaboration serves as a distinguishing characteristic within supply chains that have been empowered by Industry 4.0. The utilisation of digital platforms and loT enables stakeholders within supply chain to efficiently exchange information in a timely manner. The facilitation of an unrestricted exchange of data promotes principles of transparency, trust, and agility within network of suppliers, manufacturers, distributors, and retailers. Addressing global issues like hunger and malnutrition, producing high- quality and safe food, and ensuring awareness towards customers, society, and environment are the main priorities [10]. Social, environmental, and economic sustainability can be increased by implementing Industry 4.0 technologies throughout food supply chain [11,12]. Overall, food industry is utilising I4.0 capabilities to promote sustainable innovation and shape way food is produced and consumed in the future [12].

Sustainability and its role in driving innovation within food industry must prioritise sustainable innovation to effectively tackle major problems posed by the increasing global population and environmental concerns. The concept encompasses strategies aimed at reducing resource waste, optimising production processes, ensuring ethical sourcing, mitigating carbon emissions, and satisfying preferences of environmentally conscious consumers [7]. Sustainable innovation provides a viable approach for production of food products that are characterised by improved health benefits, ethical sourcing practises, and reduced environmental impact. The incorporation of environmentally friendly, nonthermal technologies, such as pulsed electric field, high-pressure processing, cold plasma, ozone, and electrolysed water, is imperative for the food industry to mitigate energy consumption in various stages of food production, processing, and packaging. Furthermore, it is imperative to transition towards sustainable diets that possess qualities of being cost-effective, nutritionally beneficial, and favoured by consumers. To effectively implement sustainable innovation within food industry, companies must adeptly navigate and address tensions arising from this process, while also integrating external factors into their strategies [6,13]. To address concerns regarding sustainability, taste, and cost, it is imperative to implement transformative changes within food systems and supply chains. To encourage establishment of sustainable food systems, it is essential to adopt a systems-based approach that considers complex structure of food value chains, as well as crucial part played by food processing and preparation. Eco-innovation strategies, social marketing, and branding are crucial factors in promotion of sustainable products and services within food industry [14,15].

1.2 Sustainability Influences on Food Industry

The integration of I4.0 and sustainable innovation within food industry is of utmost significance in tackling major issues and offering valuable perspectives. The food industry is currently dealing with sustainability challenges, requiring an examination of the potential impacts of I4.0 on sustainability within food sector [16]. The integration of sustainable practises has emerged as an essential element in achievement and competitive advantage of businesses operating within food industry [7].

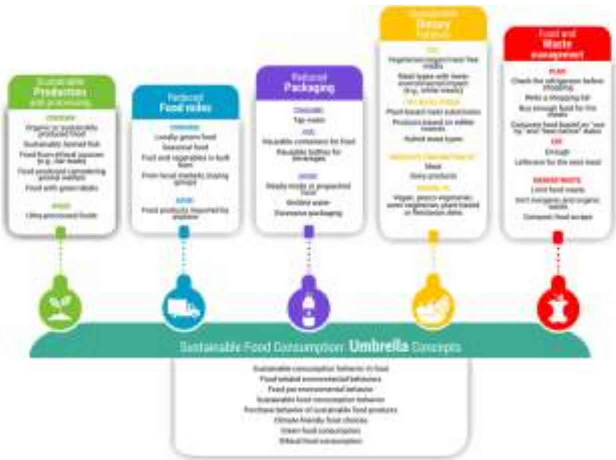

Figure 2. Categorisation of Sustainable Food Consumption (SFC) [17]

The primary objective is to investigate strategies employed by companies in effectively managing natural conflicts arising from sustainable innovation. Additionally, this research aims to identify key factors that contribute to successful implementation of sustainable innovation within organisations [15]. Also, the research focuses on exploring capabilities of environmentally friendly, nonthermal technologies to mitigate energy usage within realms of food production, processing, and packaging [6]. Additionally, the research provides a comprehensive overview of existing body of knowledge regarding 14.0's potential impact on supply chain management, specifically in relation to the triple bottom line concept of sustainability [18]. This study offers valuable insights into concept of sustainable innovation and its implications within food industry, encompassing environmental and economic considerations.

1.3 Industry 4.0 in Food Industry

To improve sustainable practises, industry 4.0 technologies—including digital ones, data analytics, automation, and loT—are being incorporated into food sector. These technologies are utilised in various stages of the food supply chain, including production, processing, distribution, and consumption. Throughout supply chain, the objective is to increase resource efficiency, reduce waste, ensure ethical sourcing, and lessen environmental effects [19-22]. The food industry can benefit from real-time optimisation, product traceability, effective logistics, and legal status authentication by utilising Industry 4.0. However, there are obstacles to be overcome, such as user acceptance issues, technological constraints, and regulatory restrictions. The potentials and difficulties of implementing Industry 4.0 technologies in food industry require more investigation. While incorporation of Industry 4.0 in sustainable practises of food industry is a worthwhile area of study, there are some constraints that must be recognised. Real-time data accessibility is a significant drawback that can differ depending on how prepared individual food industry segments are to adopt Industry 4.0 solutions [16]. The food industry is diverse, with various subsectors having traits and difficulties. As a result, future research should consider a more concentrated examination of subsectors to understand their integration of Industry 4.0 and sustainable practises [16].

This research examines and evaluates Industry 4.0's technologies in food sector, emphasising ways in which these innovations support sustainability and innovation. The ultimate objective is to provide insightful information that can support more general sustainability objectives within the food industry, improve operational efficiency.

The key research objectives the research aims are:

1. Applications and potential advantages of main Industry 4.0(14.0) technologies being used in food industry at present.
2. 14.0 technologies, that focus on waste reduction, resource efficiency and environmental impact that promotes sustainability in food production.

3. Consider social, economic, and environmental factors to evaluate the opportunities and challenges of implementing 14.0 technologies for sustainable innovation in food industry.

This paper aims to analyses the extent to which industry standards and regulations are in accordance with technological advancements. This study aims to examine impact of emerging technologies and practices on future path of food production and distribution. The research's contributions and potential effects can be seen in many different contexts. By bridging knowledge gap and providing empirical data, this study aids in the academic understanding of Industry 4.0's role in innovation of sustainable foods [20]. The recommendations resulting from this study provide useful direction for industry stakeholders, assisting them in navigating difficulties of interesting industry 4.0 technologies for environmentally friendly practices [23]. In the end, study has the potential to affect positive change by supporting for more environmentally friendly and sustainable practises within food sector [6].

2. Literature Review

The integration of Industry 4.0 and sustainability in food industry holds promise for transformative changes in operational practises, environmental adaptability, and fulfilment of needs of society. Food industry, as a prominent sector encompassing scope, investment, and diversity, is continuously adapting to respond to both requirements and consumer preferences. The goal of sustainability within agri-food sector has prompted recognition and utilisation of waste and byproducts from food industry. This practise aims to create valuable ingredients while also maintaining nutritional quality.

2.1 Industry 4.0

Industry 4.0 is latest phase in the progression of industrial revolutions, characterized by integration of digital technologies, loT, and artificial intelligence into manufacturing processes [24]. It represents a pivotal moment where cyber-physical systems (CPS), data analytics, and connectivity converge to redefine how industries operate [25]. Concept of Industry 4.0 builds upon previous industrial revolutions, including first industrial revolution in late 18th century that introduced mechanization through steam power, second revolution started in late 19th century that brought about mass production through electricity and assembly lines, and third industrial revolution begin in mid-20th century that emerged with introduction of computers and automation [26]. Industry 4.0 encompasses innovative technologies such as robotics, big data, cloud computing, and additive manufacturing, and it is expected to have significant social, economic, and industrial implications [27,28].

Figure 3. Industry 4.0 Nine Pillars [29]

Food industry has undergone significant changes due to technological advancements and evolving consumer preferences for food. Automation and digital technologies have revolutionized food processing, leading to increased efficiency and quality control [30]. Innovations such as pasteurization, refrigeration, and packing have transformed food preservation and distribution [9]. However, industry now faces new challenges related to sustainability, transparency, and meeting demands of digitally connected consumers [10]. Convergence of Industry 4.0 technologies with food industry provides an opportunity to address challenges like Data-driven insights, smart packaging, and precision agriculture. This can help sustainability, enhance transparency, and meet consumer demands [12]; [31]. The integration of technology and food industry represents a pivotal moment for food sector. The literature review holds a leading role in our research, as it carries substantial purpose and significance in the field of sustainable innovation in food industry. Review provides guidance on integration of Industry 4.0 and sustainability in food sector. The review revolves around several primary objectives, with primary objective being advancement of knowledge in field of sustainable innovation management [32].

Objective of this work is to establish a strong foundation, encompassing both theoretical and practical aspects, for incorporation of sustainable practises and principles into fundamental processes of innovation within food industry.

The overview performs an examination of potential research directions within scope of a sustainable food supply chain [6]. It also highlights significant recognition of essential part played by food supply chain in promoting sustainability. This study aims to explore and analyse relevant academic research to gain a comprehensive understanding of complex strategies, challenges, and potential benefits associated with strengthening a resilient and sustainable food supply chain. In addition, the study explores into factors that drive innovation within food industry [33]. Knowing these factors are crucial, as they function as driving force that drives innovation, ultimately impacting industry's transformation. Through a careful examination of these driving forces, this analysis aims at explaining different circumstances and motivations that drive innovation within food industry. The literature review includes examination of changing environment of sustainable dietary options and constantly shifting grouping of consumers [34]. The incorporation of sustainable dietary preferences among consumers and classification of these individuals into separate categories play a crucial role in shaping course of food industry. The primary objective of this investigation is to demonstrate multiple patterns, underlying motivations, and subsequent outcomes associated with shift towards sustainability. It provides valuable insights into ways in which businesses can adapt to meet changing expectations of consumers and effectively respond to these shifts within sector. The significant issue of food loss and waste in food supply chains is thoroughly examined in this evaluation [35]. The success of sustainability objectives is dependent upon effectively addressing this challenge. Our study aims a contribution to academic discussion on waste reduction and integration of digital technologies into food supply chains by conducting a comprehensive analysis of root causes, consequences, and possible solutions related to this issue.

2.2 Industry 4.0 Effects on Food Supply Chains

The literature review holds an important place in our research as it establishes foundation for understanding complex relationship between Industry 4.0 technologies and sustainability practises in food industry. The main aim of our research is to discover valuable insights, recognise emerging trends, and address current gaps in existing literature. Many essential studies have made substantial contributions to our understanding. Research conducted by [36] offers valuable insights into impact of Industry 4.0 on sustainability of food production. Focus of literature review is to examine/investigate the influence of knowledge application, and efficiency improvement on sustainability of food supply chains. Through this analysis, a thorough comprehension of how Industry 4.0 can contribute to enhancing sustainability of food supply chains is provided. Studies by [37] explored pragmatic implications of I4.0 in specific domain of food supply chains, placing particular emphasis on utilisation of knowledge and enhancement of operational efficiency. This research undertakes a comprehensive examination of impact of technological foundations of Industry 4.0 on operational efficiency of supply chains in small and medium-sized enterprises (SMEs). The study aims to provide insights into potential advantages and challenges associated with development of I4.0.

Figure 4. I4.0 Technologies and Food Supply Chains [38]

In addition, study carried out by [39] focuses on various pathways of a sustainable food supply chain, with a specific emphasis on examination of management challenges and dimensions of sustainability, food This research enhances our comprehension of sustainable practises in food supply chain and their broader implications for sustainability, thereby offering significant insights for development of more resilient and environmentally friendly supply chains. The academic research of [40] enhances existing body of literature by providing a comprehensive overview of field of sustainable development within context of Industry 4.0 framework. This study emphasises significance of triple bottom line, sustainable business models, and circular economy as crucial areas of research. It provides a comprehensive perspective on diverse aspects of sustainability within framework of I4.0 [41].

2.3 Integration of Sustainability, Industry 4.0, and Food Production

The literature review reviews a diverse range of scholarly publications, beginning with an in-depth analysis of fundamental concepts that are crucial to our research, including I4.0 and sustainability [42]. The introduction serves as foundation of our study, providing a comprehensive theoretical framework that directs our entire research endeavour. Going in addition to theoretical discussions, our review shifts its focus towards practical aspects by examining previous research that explores practical applications of I4.0 in food industry.

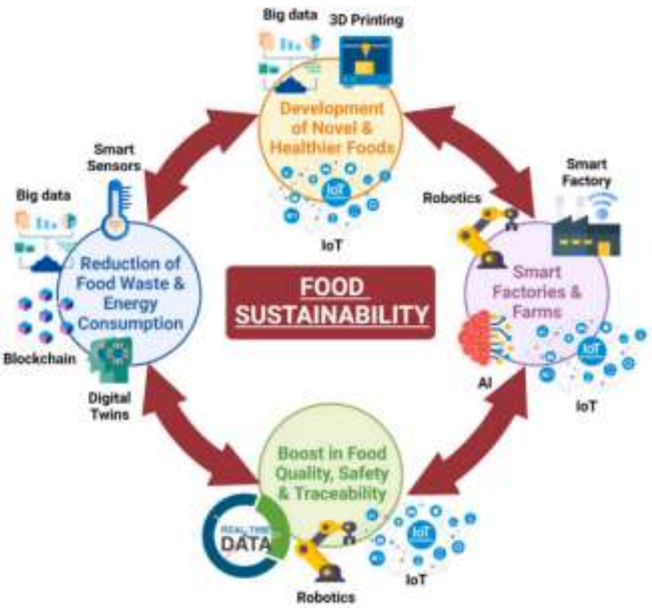

Figure 5. Industry 4.0 technologies and food sustainability-related topics [43]

Additionally, we explore sustainable innovations that have been encouraged within this sector [23,44]. The mentioned organisational structure illustrates our thoughtful technique, guiding readers through theoretical underpinnings and practical applications of these concepts [45]. In introductory section, we establish foundation for our comprehensive examination of literature, emphasising complex relationship between I4.0 and sustainability in food industry [46]. This intersection in our literature review holds significant importance as it plays a fundamental role in achieving our wider research objectives. An understanding of how Industry 4.0 can be utilised to advance sustainability in the field of food production is of utmost significance. Furthermore, this section functions as a guide for readers, allowing them to effectively navigate complex landscape of subsequent literature review with a clear sense of direction. This improves user understanding and engagement with the subject.

2.4 Theoretical Framework: RBV-TBL Synthesis

The foundation of this research is based on a strong theoretical framework that effectively integrates two essential paradigms: Resource-Based View (RBV) theory and Triple Bottom Line (TBL) framework. RBV theory, which serves as a fundamental basis for our theoretical framework, provides a comprehensive perspective for analysing and understanding complex impact of I4.0 technologies on sustainability practises and overall effectiveness environment in rapidly evolving food sector [9]. On the other hand, TBL framework, which is an essential component of our theoretical framework, thoroughly examines and investigates complex relationship that takes place between economic, social, and environmental aspects of corporate responsibility [16]. Through seamless integration of these two well-established theoretical frameworks, our research endeavours to undertake a thorough exploration of challenging diverse connection that exists between I4.0 and sustainability in diverse field of food sector. The incorporation mechanism produces an initial and ultimate purpose. Our primary objective is to provide a comprehensive framework that overcomes surface knowledge, by exploring various mechanisms through which I4.0 technologies can be optimally utilised to drive sustainable practises in challenging food supply chain. Additionally, our objective is to enhance overall efficiency and excellence of food sector by establishing an effective balance between technical improvements and sustainable practises within all aspects of supply chain. This two-layered approach enhances not only our understanding of theory but also establishes way for real-world applications and future research in challenging environment of sustainable innovation in food sector [47,18].

2.4.1 Resource-Based View (RBV)

Within the field of strategic management, Resource-Based View (RBV) theory provides a fundamental framework that forms basis for investigation of I4.0 technologies and their essential role within food industry. This theory suggests that organisations might gain a competitive advantage by effectively managing resources, hence developing an additional conceptual environment. In context of food industry, I4.0 technologies cover a range of revolutionary techniques such as data analytics, Automation and robotics, Cyber-Physical Systems (CPS), Additive

Manufacturing (AM), and IOT [19]. These technologies, commonly considered a driving force for operational progress, have capacity to fundamentally transform core operations of food sector. Through effective utilisation of these digital assets, stakeholders within food industry have potential to access a wide range of advantageous potential. The organisation has ability to maximise use of resources, streamline operational procedures, improve overall effectiveness, and cultivate an environment that encourages innovation [48]. RBV framework offers a valuable perspective for understanding Industry 4.0 technologies as strategic assets that facilitate sustainable innovation. Consequently, this research holds significant importance in ongoing discussions within food industry. By assessing these technologies' potential as strategic assets, we prepared atmosphere for a review of their practical uses, effects, and development of sustainable innovation in context of food supply chains. In following parts, we will explore practical implications and effects of these theoretical foundations, offering an in-depth understanding of Industry 4.0 ways in food industry.

2.4.2 Triple Bottom Line of Sustainability in Food Industry

The Triple Bottom Line (TBL) framework, which has been recognised worldwide for its contribution to evaluation of sustainability, offers a comprehensive method to assess sustainability within food business.

Figure 6. Triple Bottom Line of Sustainability [49]

This conceptual framework acknowledges and supports complicated interaction between three core dimensions: economic sustainability, environmental conservation, and social responsibility [23]. All these features together establish basis for implementation of sustainable business practises and incorporation of ethical issues. The TBL framework provides a systematic approach for assessing sustainability within food business. The approach under discussion has been specifically developed to emphasise equal significance of economic, environmental, and social performance. It serves to highlight concept that sustainable practises extend beyond limited economic factors. The influence of Industry 4.0 technology on food business is evaluated in these circumstances using TBL framework [50]. This expansion not only evaluates economic benefits, but also considers potential impacts on environmental sustainability and social welfare. The integration of Industry 4.0 technologies has major impacts that extend beyond financial considerations. These technologies have potential to significantly transform supply chain processes, minimise wastage, optimise resource utilisation, and boost product quality, while also considering their environmental and social implications. The food industry extends beyond traditional profit-driven models [51].

2.4.3 Integrating RBV and TBL Frameworks

The thoughtful incorporation of Resource-Based View (RBV) and Triple Bottom Line (TBL) framework into theoretical framework is not an advantageous occurrence; rather, it is an intentional alignment intended to provide a comprehensive and all-encompassing viewpoint for exploring complex dynamics intersection of Industry 4.0 and sustainability within food industry [52,6]. The RBV theory, which serves as an essential component of our theoretical framework, assumes an important role by knowing industry 4.0 technologies as strategic resources that have capacity to fundamentally transform structure and functioning of food sector. Data analytics, automation, artificial intelligence, and loT are just a few of digital technologies that go beyond being simple tools to become strategic resources that can lead to long-term innovation [53]. Simultaneously, TBL paradigm ensures a comprehensive evaluation of sustainability, encompassing economic viability, environmental preservation, and social responsibility. The utilisation of this all-encompassing methodology enables us to carefully evaluate impact of Industry 4.0 technologies, with a particular emphasis on concept of sustainability within food Industry beyond conventional economic factors [54]. Additionally, it includes use of ethical sourcing practises, mitigation of ecological impacts, and a dedication to social accountability. The strategic alignment between RBV and TBL framework serves as foundation for our research, providing insights into both theoretical and practical dimensions. This paper discusses strategic utilisation of industry 4.0 technologies by enterprises in food sector as transformative resources, with aim of promoting sustainable practises throughout entire food supply chain [55].

2.5 Industry 4.0 and Sustainability

The emergence of I4.0 commonly known as Fourth Industrial Revolution, represents a significant transition in manufacturing sector, identifying new beginning of an era filled with new concepts and revolutionary practises [24]. Present-day revolution is characterised by seamless integration of advanced digital technologies, decision-making approaches based on data analysis, and widespread adoption of automation. The ultimate outcome of this seamless integration is enhancement of productivity, optimisation of efficiency, and a strengthening of competitiveness across various industrial sectors [56]. The structure of I4.0 revolves around integration of significant technological trends, each of which plays a crucial role in shaping extensive impact of this revolution. These trends involve a broad range of cutting-edge technologies. The concept of I4.0 extends beyond scope of simple automation and data-driven decision-making [57].

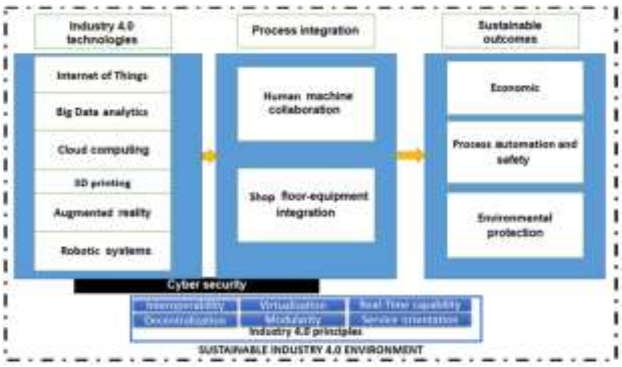

Figure 7. I4.0 Technologies and Sustainable Outcomes to Environmental Sustainability [58]

Concept involves development of advanced intelligent factories and manufacturing systems that not only operate independently but also possess ability to acquire knowledge, engage in logical reasoning, and autonomously optimise their operations. The incorporation of digital technologies enables these intelligent systems to efficiently monitor, assess, and react to data in real-time. Outcome is an improvement in production processes, reduction of operational inefficiencies, and a significant decrease in errors [57]. Primary goal of I4.0 is to fundamentally transform current business models and optimise manufacturing efficiency through strategic integration of digital technologies and automation. By effectively leveraging data and automation, organisations can enhance operational efficiency, reduce costs, improve quality standards, and effectively respond to market demands [25].

2.5.1 Sustainability as Comprehensive Approach

The concept of sustainability within food industry encompasses a comprehensive effort that aims to strike a balance current need with responsible management of resources, ultimately aiming to benefit future generations [13,14]. Primary scope of this comprehensive concept extends well beyond a narrow focus on environment, encompassing a diverse range of factors that profoundly influence fundamental structure of our food systems [30]. Fundamental essence of sustainability within food industry is centred on three distinct yet closely interconnected dimensions environmental, social, and economic [59]. The mentioned aspects play a crucial role in establishing a sustainable food system, and it is essential to address them collectively to achieve sustainability [60]. Food industry has a wide range of considerations to make when maintaining the sustainable path. It must deal with challenges of lowering greenhouse gas emissions, minimising land use, protecting biodiversity, managing water resources, ensuring access to affordable food, maintaining cultural relevance, and placing a priority on public health [30]. Furthermore, it is crucial to emphasise significant role played by food value chain, which includes food processing and preparation, in facilitating transition of our current food systems towards a more sustainable path. This sector of industry plays a crucial role in developing solutions that are in line with sustainability objectives [14]. To navigate this complex and diverse environment effectively, it is essential for both the food industry and sustainability researchers to collaborate to establish universally recognised definitions and comprehensive indicators of sustainability. This collective endeavour functions as a guiding principle in shift towards more sustainable food systems, with goal of achieving an optimal balance between present requirements and conservation of resources for future generations.

2.5.2 Environmental Sustainability

Advancement of environmental sustainability within food industry involves an extensive number of strategies that are designed to mitigate its ecological consequences. A primary objective revolves around reduction of greenhouse gas emissions through implementation of improved energy efficiency practises and utilisation of carbon storage techniques [7]. Efficient allocation of resources, encompassing management of water, optimisation of energy usage, and preservation of land and soil, is of highest priority [13]. There is a significant focus on reduction of food waste, with attention being given to addressing this issue at each stage of supply chain [61,62]. Individual's data is not sufficient to be rewritten in an academic manner. Sustainable packaging solutions place emphasis on reduction of materials, utilisation of recyclable and biodegradable materials, and minimization of waste [63].

The emergent rise of digitalisation through the context of I4.0 enables manufacturing industries to further advance the digital transformation within the firm. It also allows future opportunities for manufacturing firms to focus on performance while having environmental impact. Although, the key focus for firms is on product lifecycle that also was evident through the existing studies within the literature. Figure presents the provide value chain of product and technology lifecycle model [64].

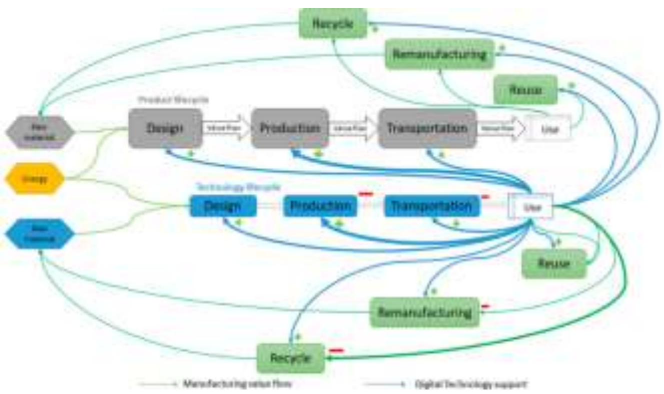

Figure 8. Value Chain of Product and Technology Lifecycle [64]

Implementation of sustainable agricultural practises, such as organic farming and reduction of pesticide usage, helps promote well-being of soil and preservation of biodiversity. Preservation of biodiversity is of utmost importance, considering significant influence that agriculture has on traditional ecosystems. Incorporation of I4.0 capabilities serves to improve environmental sustainability within food industry, utilisation of loT sensors and analytics in resource management enables a data-driven approach that enhances allocation of resources and minimises wastage [22]. Implementation of I4.0 technologies, such as drones and smart farming equipment, has been observed to enhance precision agriculture and optimise resource utilisation [19]. While implementation of automation and robotics technologies has been shown to improve operational efficiency and mitigate waste [65]. Utilisation of additive manufacturing facilitates creation of customised and environmentally sustainable packaging solutions [66]. Provision of supply chain transparency enables consumers to make well-informed choices regarding sustainable products [12]. Integration of se technological advancements, in conjunction with implementation of sustainable practises, serves to foster a heightened environmental awareness and enhanced resilience within food industry. This approach aims to achieve an ideal balance between technological innovation and ecological management.

2.5.3 Economic Sustainability

Economic sustainability within food industry is an important basis that supports financial stability and long-term sustainability of businesses involved in different aspects of food production, processing, and distribution. At its essence, concept of profitability arises as a crucial factor in ensuring economic sustainability. Concept holds significance beyond just financial revenues, as it encompasses core values of businesses, guaranteeing their capacity for investment, grow, and establish long- lasting sustainability [7]. Mentioned concept can be seen in practise of ensuring fair distribution of profits, which is observed across all stages of supply chain. This approach places significant emphasis on principle of distributing rewards in a manner that is shared among all relevant stakeholders. This ensures that all parties involved, ranging from initial producers to final distributors, are provided with a just and ethical share of economic advantages [13].

Overall well-being of employees represents an additional fundamental aspect of economic sustainability, encompassing essential elements such as equitable remuneration, secure industrial environments, and availability of social welfare programmes. The importance of health of people involved in industry has a direct impact on productivity and efficiency of workforce, thereby contributing to a content and healthy work environment [67].

An industry that prioritises economic sustainability does not limit its dedication to this aspect alone. This highlights importance of market entry for small-scale and local producers, thereby promoting their financial stability while advocating for fair opportunities within industry. The effective use of I4.0 capabilities has potential to enhance economic sustainability within food industry through a range of methods. To begin with, it is important to note that implementation of I4.0 technologies has potential to optimise utilisation of resources, resulting in a reduction in production costs and an overall improvement in profitability [3]. Also, implementation of smart supply chains guided by principles of I4.0 has been shown to enhance operational efficiency, minimise resource wastage, and facilitate market entry, thereby making a significant contribution to achievement of economic sustainability [68,9]. In addition, utilisation of blockchain technology and data analytics facilitates establishment of transparent and traceable supply chains, thereby promoting equitable trade practises and just pricing mechanisms for producers operating on a smaller scale [69]. Furthermore, implementation of automation and robotics in context of Industry 4.0 leads to a decrease in tasks that require significant human labour, resulting in enhanced efficiency and productivity in workforce, all while prioritising welfare of workers [11]. Utilisation of I4.0 technologies has enabled small-scale and local food producers to enhance their market reach through digital platforms and e-commerce.

2.5.4 Social Sustainability

In the challenging world of sustainability within food industry, social sustainability plays a significant role in preserving wellbeing of people and communities involved in food production and consumption. Main goal is to make sure that industrial activities benefit society while also preserving welfare and way of life of individuals and communities. There are numerous factors and tactics that work together to promote social transformation and strengthen sustainability principles in the context of I4.0 era and goal of sustainable innovation.

Figure 9. Components and Dynamics of Corporate Social Sustainability and Innovation [70]

A primary area of emphasis within suburban communities revolves around enhancing public consciousness regarding significance of food sustainability. Utilisation of I4.0 technologies presents a robust method for effectively spreading this awareness, by capitalising on digital platforms and communication channels to instruct and involve public in sustainable food practises [71]. Essence of social sustainability lies in establishment of collaborative cooperation, which has been greatly facilitated by emergence of I4.0. This development has effectively promoted collaboration among a wide range of stakeholders, encompassing government agencies, corporations within food industry, academic institutions, and local communities. As a collective, individuals possess capacity to participate in decision-making processes related to programmes designed to promote empowerment and social initiatives. The integration of data, analytics, and digital platforms enables the implementation of data-centric decision-making processes, thereby facilitating the development of programmes that are more effective and equitable. Consequently, this encourages positive results for society [32]. Regardless of whether they are involved in Business-to-Business (B2B) or Business-to-Consumer (B2C) transactions, companies operating in the food industry are increasingly incorporating sustainability discourse into their social media communications.

B2B enterprises place a high level of importance on well-being of their employees, whereas B2C companies adopt a more balanced approach that considers both economic and social dimensions. Utilisation of I4.0 technologies has a substantial impact on improvement of communication endeavours, facilitating efficient engagements with consumers and stakeholders [72]. Incorporation of technological capacities, such as communication infrastructure and logistic optimisation, holds significant importance in improving sustainability of supply chains within food industry entities [73]. Moreover, capabilities of I4.0 have potential to greatly enhance social sustainability within food industry. Implementation of automation and robotics technologies has resulted in a decrease requirement for labour-intensive and physically demanding tasks, thereby improving safety and well-being of workers [74]. Implementation of I4.0 technologies, such as blockchain and data analytics, serves to establish supply chains that are characterised by transparency. This transparency, in turn plays a crucial role in ensuring equitable compensation for small-scale producers and workers [75]. Utilisation of digital platforms and availability of real-time data offer enhanced opportunities for individuals to access information, thereby enabling consumers to make well-informed decisions regarding ethically produced food products [76]. Development of I4.0 has been instrumental in promoting enhanced interaction between food producers and local communities, thereby cultivating favourable associations and encouraging social accountability [75]. Furthermore, additive manufacturing plays a crucial role in facilitating creation of culturally significant food products and packaging, thereby contributing to preservation and continuation of traditional recipes [77].

2.6 I4.0 Components Application in Food Sector

2.6.1 Internet of Things (loT)

The concept of interconnectivity, a fundamental principle of I4.0, serves as a crucial element in establishing real-time connections between machines, devices, and systems within complex network of food supply chain. This principle goes beyond simple technological integration and has a significant influence on fundamental structure of food industry. It coordinates an effective blend of operational optimisation and sustainability improvement. loT is a key component of I4.0 initiatives and is emerging as fundamental infrastructure supporting intelligent manufacturing and distribution systems [78].

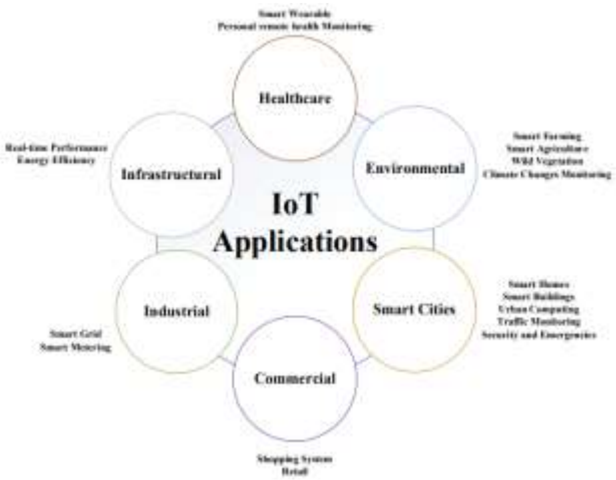

Figure 10. Taxonomy of IoT Applications [79]

In context of food industry, loT plays a crucial role in facilitating connectivity by utilising sensors to effectively collect data related to factors such as temperature, humidity, and state of products [78]. Real-time exchange of data in this system enables stakeholders to make proactive decisions, which in turn reduces spoilage, waste and ensures preservation of product quality [80]. The importance of interconnectivity is evident in its ability to facilitate smooth coordination in field of food production, enabling flexible adaptations, production processes and adoption of just-in-time restocking approaches. As a result, continuing problems of bottlenecks and overstocking are reduced, thereby promoting an environment advantageous to smooth operational processes [81]. Possibilities of loT are not limited to production alone, but also encompass consumer engagement by leveraging smart packaging and labels. By providing consumers with information about origin, freshness, and sustainability of products, these innovative approaches increase consumer trust and enable informed decision-making [11]. Furthermore, many different and numerous contributions of loT extend beyond boundaries of simple operational efficiency. Advancement of sustainability is facilitated through optimisation of operations, reduction of waste, improvement of transportation and logistics, minimization of energy usage, and enhancement of overall resource efficiency [82]. Also, it provides substantial backing for ethical and sustainable sourcing practises by providing stakeholders with a transparent view of complexities involved in supply chains.

2.6.2 Big Data and Analytics

Within framework of I4.0, combination of data analytics and big data takes a crucial position, coordinating a comprehensive process encompassing data collection, storage, processing, and generation of transformative insights. Integration of various technologies plays a crucial role in supporting data-centric ideology of I4.0, which forms foundation for all aspects of food supply chain. I4.0 represents an evolution in data collection techniques. By employing a complex network of sensors and interconnected systems, it coordinates collection of extensive and diverse datasets at different stages of food supply chain [83,84].

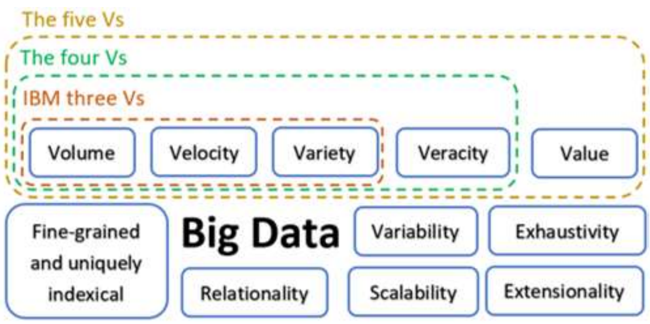

Figure 11. Characteristics of Big Data [85]

Mentioned data streams flow into secure databases, frequently residing within cloud-based platforms, to guarantee their availability for subsequent analysis [86]. Within realm of data analytics, concept of I4.0 utilises a diverse range of advanced technologies, including machine learning and artificial intelligence algorithms, to effectively analyse and evaluate extensive volumes of accumulated data. To get raw data ready for its upcoming role as an informant for decision-makers, this analytical engages in dynamic activities like data cleansing, collection, and organising [87]. The impact of data analytics extends to domain of quality control and system described in text serves as a real-time monitor for ensuring quality of food products. Equipped with capability to identify irregularities and variations during each step of production, it effectively prevents distribution of inadequate items in market [88]. The field of data analytics has given rise to concept of predictive maintenance, which involves utilising sensor data to proactively anticipate and prevent machine failures. Implementation of strategic insight enables timely maintenance of systems, thereby preventing disruptive breakdowns in supply chain and developing an environment characterised by reliability and consistency [87]. Within context of sustainable innovation in I4.0, data analytics plays a key role, encompassing various aspects of food supply chain. The phenomenon serves as driving force for waste reduction, resource optimisation, informed decision-making for sustainable packaging, evaluation of supply chain sustainability, exploration of consumer behaviour. It provides valuable insights that guide sustainable marketing and product design strategies towards a more sustainable future.

2.6.3 Automation and Robotics

Automation and robotics play a crucial role in context of I4.0, offering considerable advantages across various industries, including food sector, which experiences significant benefits. Automation in food industry refers to effective incorporation of machinery, robotics, and control systems to carry out a diverse range of activities, including but not limited to packaging, labelling, sorting, and food production functions [89].

Figure 12. Automation and Robotics in Manufacturing

The distinguishing characteristic of robotics and automated systems lies in their consistent precision, which makes them exceptional in terms of accuracy and product quality [90]. Consequently, they enable efficient completion of tasks that require significant labour, thereby reducing need for human involvement and resulting in cost savings [91]. The systems demonstrate their versatility by being easily scalable to meet production requirements thereby serving as a flexible solution for dynamic demands of food industry [92].

In addition to their ability to achieve high levels of accuracy, automation and robotics play a crucial role in collection of real-time data, which offers a valuable dataset for quality control, process optimisation, and prediction of maintenance requirements [93]. Automation and robotics are in accordance with principles of sustainable innovation. They have a significant impact on reducing food waste, maximising efficient use of resources, advocating for sustainable packaging methods, improving food safety regulations, and strengthening traceability throughout food supply network.

2.6.4 Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) have emerged as a breakthrough integration of physical operations with digital control and communication in food industry, enabling real-time monitoring and control capabilities throughout every aspect of food supply chain [94]. These systems depend on a complex system of sensors that are specifically engineered to collect and transmit data related to crucial parameters such as temperature, humidity, and pressure.

Figure 13. Physical and Digital World Connection [96]

A key feature of CPS is its ability to integrate and analyse data in real-time, providing a comprehensive perspective on entire production and distribution processes [95]. Utilising extensive dataset available, CPS systems have capability to make instantaneous decisions and take actions, such as changing cooling systems or adjusting conveyor speeds, to establish an optimised operational setting. In addition, CPS systems utilise predictive analytics to anticipate potential problems and take proactive measures to mitigate them before they develop [14]. Within food industry, applications of CPS are diverse and encompass various aspects. These include but are not limited to temperature and humidity control, monitoring food safety, optimising resource efficiency, ensuring quality control, and enabling traceability. These applications play a crucial role in advancement of sustainability, reduction of waste, and guarantee of consistent quality and safety standards for food products [97].

2.6.5 Additive Manufacturing (AM)

Additive Manufacturing (AM), also referred to as 3D printing, is an innovative manufacturing method that fabricates real-world products by sequentially depositing material layers based on digital 3D models. In context of food packaging, AM emerges as a significant contributor in reduction of waste and promotes sustainability. In the foundation, AM demonstrates exceptional proficiency in area of customization. Utilisation of this technology enables exact customization of packaging for individual products, considering their distinct shape and size. As a result, amount of excess packaging material is minimised, representing a significant advancement in waste reduction [98].

Figure 14. Traditional Vs. Additive Methods [99]

In addition to offering customization options, AM provides capability to create packaging designs that possess desirable qualities of being lightweight and robust. This trend not only results in a reduction in overall weight of packages, but it also contributes to a decrease in transportation costs and emissions. These outcomes correlate with fundamental principles of sustainable packaging [100]. AM also promotes towards ideal of minimal waste. The utilisation of minimal materials in design process leads to a significant reduction in waste generation, thereby eliminating requirement for extensive removal of materials during post-production [101]. Furthermore, utilisation of technology enables exploration of innovative packaging configurations. Mentioned designs effectively maximise strength, insulation, and protection, thereby minimising use of materials. This significant achievement greatly contributes to development of sustainable food packaging [102]. Benefits of AM are enhanced by its use for short production runs and quicker development. This capability facilitates the production of goods as needed and in specific locations, thereby diminishing need for extensive, centralised manufacturing plants and promoting sustainable practises [103]. Subsequently it is important to acknowledge that AM has capability to utilise biodegradable and environmentally friendly materials for the purpose of food packaging. This aligns perfectly with larger sustainability objectives and represents a significant advancement in advancing development of packaging solutions that are environmentally safe.

2.7 Industry 4.0 and Sustainable Innovation

The incorporation of 14.0 technologies by food industry has resulted in increased production efficiency, enhanced quality control, and establishment of a reliable traceability system [104]. Furthermore, these technologies have made substantial contributions towards reduction of waste and enhancement of overall productivity [3]. Prior studies have utilised various methodological strategies, such as comprehensive case studies and surveys, to comprehend adoption trends and consequences of specific I4.0 technologies within food industry [21,9]. A notable development that has arisen is growing significance of loT within food industry, facilitating collection of real-time data and facilitating smooth communication throughout supply chain [11]. Several technologies have undergone study in recent times, including utilisation of loT for monitoring supply chains, application of data analytics for predicting demand, and the implementation of automation and robotics to enhance food production processes. Previous research efforts have played a crucial role in shedding light on complex and diverse nature of sustainable innovation in food industry. These studies have conducted a thorough investigation that encompasses all aspects of food production, processing, distribution, and consumption [40].

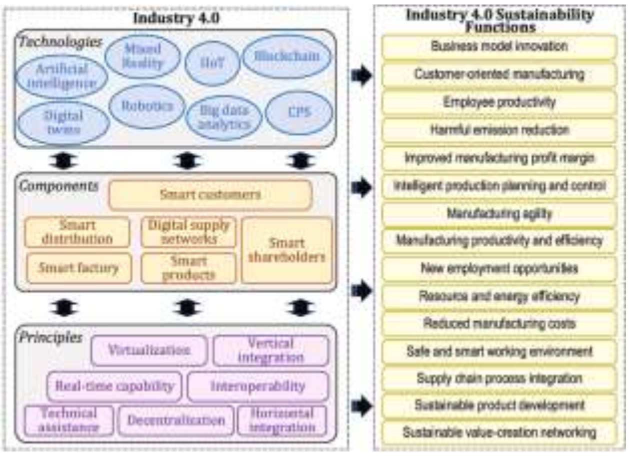

Figure 15. I4.0 and Sustainability Functions [105]

The research methodologies utilised in these investigations have exhibited significant diversity, including quantitative assessments that examine complex nature of environmental impact and comprehensive case studies that analyse specific examples of sustainable food production processes [20,6]. The exploration of underlying factors that drive sustainable innovation in food industry has been a recurring and significant focus in this research. These investigations have provided insight into various factors that drive industry towards sustainability. These factors include regulatory requirements, increasing consumer demand for environmentally friendly products, and industry's strong need to reduce environmental impact of food production. Understanding complex nature of these driving forces is crucial, as they form fundamental basis of the food industry's shift towards sustainability [10]. These forces govern industry's operations and significantly influence decisions made by both producers and consumers.

2.8 Research Gaps

The current state of literature on I4.0 potential to support sustainable innovation in food industry reveals an apparent lack in thorough analysis of 14.0 technologies that have enormous potential in this context. Additive manufacturing, also known as 3D printing, has potential to greatly reduce food waste, particularly in area of packaging. However, it is interesting to note that this technology has received relatively little attention in existing research efforts [104]. Within wider framework of sustainability in food industry, there is a significant focus on aspects such as sustainable sourcing strategies and innovative production techniques, both of which are clearly of greatest significance. The often ignored but profoundly important environmental factors that cross complex landscape of food supply chain, however, stand out as a noticeable gap in this wide domain. The review of factors such as temperature and humidity, which undoubtedly have a significant impact on maintaining safety and quality of food products, presents itself as a subject that warrants more extensive and thorough investigation [15]. To address current lack of research in this area, it is necessary to conduct a comprehensive investigation into technologies associated with Industry 4.0. This will shed light on the less visible aspects of these technologies, which may play a crucial role in promoting sustainability within food industry [32].

The current gaps in academic research related to Industry 4.0 and its impact for sustainability within food industry provide an important barrier to obtaining a thorough understanding of how these technologies can be optimally utilised to advance sustainability endeavours [25]. Knowledge gaps in question are characterised by their diverse nature, as they encompass various critical dimensions. First and foremost, it is evident that there is a significant lack of thorough investigation into specific technologies associated with I4.0, which have capacity to greatly contribute to sustainable innovation within food industry. Considerable research has been dedicated to concept of I4.0 in a comprehensive manner. However, specific technologies that have potential to significantly contribute to sustainability have not been given appropriate level of attention they deserve [128]. A few examples application refers to additive manufacturing, commonly referred to as 3D printing, and its relatively unexplored potential in mitigating food waste derived from packaging [28].

Furthermore, there exists a noticeable gap in addressing essential environmental factors within food supply chain, in addition to limited examination of specific technologies. Frequently, conversations pertaining to sustainability within food industry revolve around examination of sourcing practises and production methods. Although those mentioned variables undoubtedly hold significant importance in sustainability initiatives, there appears to be a noticeable gap concerning environmental circumstances within supply chain. The control of temperature and humidity is crucial for maintaining quality and safety of food [106].

However, there is a lack of research on this topic. Industry's failure to adequately investigate and understand precise capabilities of 14.0 technologies, coupled with its lack of concern for crucial environmental factors, could hamper its ability to fully exploit potential of these innovations in its sustainability endeavours. Therefore, it is crucial to address these flaws. The research endeavours to broaden its scope by addressing an additional overlooked aspect of sustainability in food industry, specifically emphasising environmental factors present in supply chain. These insights possess not only theoretical value but are also expected to provide industry stakeholders, such as decision-makers and producers, with practical tools and knowledge to improve their sustainability and innovation practises.

3 Methodology

The scientific method used to examine and evaluate Industry 4.0's potential for sustainable innovation in food sector is described in methodology section of this study. This chapter encompasses a comprehensive integration of multiple components that comprise research process, encompassing research philosophy, research approach, Reliability and Validity, data collection, data analysis, ethical consideration and time horizon.

3.1 Research Process

The most important part of this study centres on the examination of practical applications of Industry 4.0 in food industry, with a specific focus on sustainability goals such as mitigation of food waste resulting in improved energy efficiency. Although there is a significant amount of research focused on application of I4.0 across different sectors, there is a noticeable gap in comprehensive analysis of its specific implications for sustainability in food industry. The main objective of this study is to gather knowledge from various sectors within food industry, to enhance our comprehension of potential of I4.0 in promoting sustainable innovation. Additionally, this research seeks to tackle pressing concerns like food waste and energy conservation. As highlighted earlier, there is a noticeable research gap that underlines need to investigate utilisation of I4.0 capabilities in promoting sustainable innovation within food industry. The study is to gather data regarding sustainable practises available in food industry.

However, it also examines wider implications of I4.0 capabilities in relation to sustainable endeavours. Several factors, including limited availability of resources, challenges in accessing desired data sources, and imperative to complete the research within a specified timeframe. The adoption of secondary data analysis is viewed as an appropriate strategy to ensure advancement and successful completion of study. Although primary data collection was initially favoured, constraints forced a greater focus on utilising secondary data.

3.2 Research Approach

Every scientific study must carefully consider its research approach because it will determine study's methodology and impact entire research process [107] propose that there are two fundamental research approaches. The deductive approach is characterised by its emphasis on the relationship between theory and research. In this approach, existing theories serve as foundation for the research process, ultimately leading to creation of ideas.

Table 1. Research Literature Keywords

Industry 4.0	“The Fourth Industrial Revolution”, “Smart manufacturing” “Digital revolution” “loT for Industry (lloT)” “Cyber-physical frameworks” “Intelligent factories” “advanced production”.
Food Industry	“Food chain and industry Food supply” “food preparation” “Precision farming Smart farming” “Intelligent planning and scheduling" “food security”
Sustainability	“Sustainability”, “Ecological methods”, “sustainability of the environment”, “environmentally friendly production”, “a chain of sustainable supplies”, “The circular economy”, “Goals for sustainable development (SDGs)”
Intersection Keywords	“The food industry and Industry 4.0", “Utilising intelligent technology in food production”, “Digitization of the food chain supply”, “Internet of Things in environmentally friendly farming”, “Ecological methods in intelligent manufacturing facilities”.

The study is conducted by researcher with aim of either supporting or denying hypotheses. The second approach can be characterised as inductive, as it involves deriving conclusions based on empirical observations. This method guides researchers in formulation of new theories and hypotheses [107, 108]. Nevertheless, it is essential to acknowledge that attaining absolute certainty is never achievable when drawing inductive inferences. In practical application, boundary between these two approaches is frequently less obvious than described in the existing body of methodology literature. According to [107], although deductive methods are commonly linked to quantitative data and inductive methods to qualitative data, it is important to note that a deductive approach can also incorporate qualitative data. Within the context of research, chosen research approach primarily adheres to an inductive methodology. This decision is based on the extensive utilisation of qualitative data and the exploration of innovative theories related to the food industry. However, it also utilises established theories to attain sustainability within the food industry through the implementation of I4.0. The research exhibits a fundamental aspect of deductive logic, as can be observed.

The qualitative approach effectively highlights individual perspectives and complies with the idea that reality is socially constructed. These are essential elements in the analysis of real-life experiences and perspectives that are inherent in secondary data. Therefore, qualitative research is preferred methodology for conducting a thorough investigation into the practical implications of I4.0 in the food manufacturing sector, as it offers the required depth and breadth necessary for this study.

3.3 Reliability and Validity

In context of qualitative research, concepts of reliability and validity hold significant importance as they contribute to credibility and objectivity of study. These concepts function as evaluative tools that measure degree of reliability within research methodology [109] proposed a categorization of reliability and validity into internal and external dimensions. Internal reliability refers to level of understanding among multiple researchers within a study group with regards to their observations. It is essential that these researchers achieve an understanding regarding their perceptions and observations throughout course of their research [109]. The presence of internal reliability within study's findings ensures their reliability and consistency. In order strengthen internal reliability of this study, this chapter provides a comprehensive account of data collection process. This level of detail allows for other researchers to replicate study under similar circumstances and achieve comparable outcomes [110].

In contrast, external reliability pertains to degree of which a study can be replicated and yield consistent findings when compared to initial investigation. Attaining a high level of external reliability can present difficulties due to potential variability in real-world conditions between initial research and any subsequent replicating efforts. However, [111] had proposed a strategy that suggests assuming an identical position to initial researcher to ensure replication of initial study. Internal validity refers to degree to which researchers can achieve agreement and arrive at comparable conclusions. The degree of correspondence between observations made by researchers and theoretical concepts formulated during course of study is indicative of measure of alignment. The utilisation of qualitative research methods, characterised by an extended period of engagement within social context, often results in a strong alignment between observed phenomena and theoretical constructs. Instead, this study will rely on existing data collected by other researchers to derive opinions and draw conclusions about diverse purchasing practises.

3.4 Data Collection and Analysis

The initial study is based on an extensive theoretical framework that has been specifically designed to suit unique circumstances of food industry within context of I4.0. To establish framework, a comprehensive review of secondary literature relevant to research topic was conducted, providing valuable insights into field of study. The utilisation of secondary data sources, such as academic books, scholarly articles, reputable websites, and company reports, formed initial phase in establishing parameters of this research and identifying variables of interest for thorough examination [112]. It is crucial to acknowledge that implementation of Industry 4.0 technologies in food industry is a developing field. Although secondary data gathered may have originated in previous years, it still serves as a reliable basis for this study, enabling us to expand upon accumulated knowledge [107]. By adopting a comprehensive theoretical framework, we can systematically examine extensive relationship between capabilities of Industry 4.0 and promotion of sustainable innovation within ever-changing context of food industry.

The methodological approach analyses secondary data that is currently available, emphasising resource efficiency, waste reduction, environmental impact, and real-world applications of Industry 4.0 in food manufacturing industry. Our data analysis methods in this qualitative study are specifically designed to systematically uncover insights and patterns that align with our research objectives. The main data source utilised in this study consists of pre-existing secondary sources, which include academic literature, reports, and associated materials [107,113]. The process begins with data familiarisation, wherein we engage in a comprehensive examination of gathered secondary data, aiming to acquire an in-depth understanding of its substance and specific context. Following this, coding phase, wherein systematically classify data, identify significant segments, and assign codes that clearly convey essence of each segment.

4 Research Findings and Discussions

This research's data analysis section, divided into three essential parts, thoroughly investigates how I4.0 technology and sustainable innovation meet in the food sector. The Literature Review explores a carefully chosen range of academic papers, concentrating on the incorporation and effects of I4.0 in food production and sustainable supply chain management. After that, the Thematic Analysis carefully selects and explains major themes, offering insights into technical developments, obstacles, and social and economic ramifications. The last section, the Discussion, critically assesses these topics, particularly on evolving practices, trends in technology uptake, and the consequences for sustainability. This analytical trip provides a comprehensive grasp of how I4.0 transforms the food business to adopt sustainable practices.

4.1 Focused Literature Analysis

To guarantee the quality and relevance of article compiled and reviewed, a rigorous selection procedure that followed predetermined inclusion and exclusion criteria was part of the literature review approach for secondary data. Articles that addressed sustainability and Industry 4.0 applications in food business and were published between 2019-2024 met the inclusion criteria. Publications published outside designated time frame, articles not in English, and articles not directly relevant to food business were excluded. Using keywords like "Industry 4.0," "sustainable innovation," and "food industry," the search approach involves querying academic sites, including Scopus, WoS, and others. Many potential articles were found in the first search, then carefully examined for relevance to the topic and abstracts. This resulted in the selection of five significant publications, which together offer a variety of viewpoints and conclusions about the contribution of I4.0 to improving sustainability in the food business. The essential themes, innovations, difficulties, and consequences for sustainable practices were then carefully extracted from each piece, serving as the foundation for the ensuing thematic analysis.

4.2 Insight from Existing Literature

Quiroz-Flores et al. (2023) extensively reviewed 436 papers, emphasizing the implications and uses of I4.0 technologies in food supply chains (FSCs). Their findings demonstrate the importance of technologies like blockchain and the Internet of Things (loT) to improve FSCs1 transparency, trackability, process optimization, and waste reduction. While some technologies, such as blockchain and loT, have a more significant influence than others, the study classifies significance of numerous Industry 4.0 tools in enhancing sustainability. It highlights those that are still underutilized in food industry. This study highlights the necessity for a balanced approach to technology adoption for sustainable innovation and sheds light on the current technological trends in the food I4.0. Studies [52]3) examines the relationship between business innovations and sustainability. They define different sorts of innovations, such as process, product, and I4.0 model innovations, and discuss how these relate to triple-bottom-line sustainability and the Sustainable Development Goals (SDGs). Although process and product innovations receive much attention, literature review shows that open and marketing innovations require more investigation [52].

Table 2 Key Findings: A Comparative Analysis

Aspect	Key Findings from My Review	Insights Obtained from Published Studies
Integration of blockchain and loT	The integration of blockchain and loT is being used to improve transparency and traceability in food supply chains.	Studies explored the integration of loT sensors and blockchain technology to mitigate security vulnerabilities and enhance traceability within food supply chains [46]
Minimising waste	loT-based monitoring technologies facilitate enhanced tracking capabilities, leading to process optimisation and decreased food waste.	Research demonstrated how supply chain monitoring made possible by loT enables improvements to be found that maximise resource efficiency and minimise food waste, investigates the use of blockchain technology and Internet of Things sensors to reduce security flaws and improve food supply chain traceability [114].
Financial obstacles	The adoption of Industry 4.0 technologies such as sensors, automation, blockchain, etc. is limited significantly by the substantial expenses involved.	The significant expenses associated with implementing active packaging solutions that act as a barrier to their adoption [114].

The study above highlights the capacity of Industry 4.0 to promote sustainable business models, increase operational efficiency, and support broader sustainability objectives. Studies by [46] developed a strategic plan outlining how Industry 4.0 may support sustainable innovation in manufacturing. Interpretive structural modelling, including enhanced cross-functional cooperation, increased capacity for green absorption, and a focus on sustainable innovation, identifies eleven essential roles of Industry 4.0. According to [46], these roles improve the potential for green process innovation and the creation of environmentally friendly products, substantially contributing to sustainable manufacturing practices.

This study offers companies a methodical way to use I4.0 to promote sustainable development. Studies [114] examined the obstacles and difficulties associated with integrating Industry 4.0 technology into agri-food supply chains. They list fifteen concerns that fall under the technical, operational, financial, social, and infrastructure categories. Extensive data management and technology architecture are the most critical problems they highlight. This article outlines the difficulties and obstacles associated with implementing Industry 4.0 in agri-food supply chains and offers a plan of action for successfully overcoming these obstacles. Studies highlights the technology's contribution to improved overall performance, energy savings, and food safety, gives an insightful analysis of Industry 4.0's application in the food supply chains [115]. A SWOT analysis is also provided in this study, highlighting the study's advantage as optimized performance and disadvantage as resistance to change management.

4.3 Thematic Analysis of the Resources

Thematic analysis is a qualitative analytical technique used to find, examine, and summarize patterns or themes in data. Thematic analysis plays a crucial role for the focused literature review with secondary data by helping to organize the many intricate findings from the literature into meaningful themes [116]. This method enables a thorough investigation of the subtleties and related elements of I4.0 contribution to sustainable innovation in the food sector. The thematic analysis provides an organized interpretation of the data by classifying & organizing the information, emphasizing the most important and recurrent themes in the chosen research.

4.4 Identification of Themes

The five articles' thematic analysis identified several important themes that highlight I4.0 diverse role in advancing sustainability in the food sector.

Figure 16. The five articles' thematic analysis

4.4.1 Technological Advancements and Innovation

The articles all touch on the multitude of technological innovations by I4.0. This covers cloud computing, big data, blockchain, cyber-physical systems, and the Internet of Things.

Table 3. Industry 4.0 Outcomes [118]

Impact	Outcomes
Economic and Environmental Impact	▪ Productivity Increase. ▪ Energy saving and CO2 emission reduction. ▪ Hygiene conditions improvement. ▪ Food quality improvement. ▪ Throughput rate and lead time reduction
Organizational Impact	▪ New business function ▪ Flexibility. ▪ Improved operations planning capacity.
Human Resource Management Impact	▪ Increased work pace ▪ Reduced workforce in some task ▪ Increased knowledge sharing. ▪ Increased production supervision
Strategic Impact	▪ Improved Strategic capacity ▪ Improved Supply-demand alignment ▪ Risk Mitigation ▪ Long term economic and environmental sustainability

These technologies have played a key role in changing customs, resulting in food production and supply chain procedures that are safer, more transparent, and more efficient [117, 46]. The effects of digitalization and I4.0 technologies were observed at various organizational levels, as illustrated in

Table 3. The technologies of I4.0 have had a beneficial impact on quality of products, effectiveness of processes, and capacity for strategic planning [118].

4.4.2 Integration of Sustainability to I4.0 Models

An additional theme emphasizes how Industry 4.0 advances enable sustainability into business strategies. Authors highlights the importance of I4.0 in promoting sustainable business models and accomplishing SDGs [52]. This is also discussed in [115] study, which addresses how these technologies might help reduce waste and energy use and improve environmental sustainability.

4.4.3 Challenges and Barriers to Implementation

Notwithstanding the possible advantages, many obstacles to overcome in adopting I4.0 technology exist. These include data management and security challenges, resistance to change, high prices, and complex technological concerns [114]. These difficulties draw attention to the necessity of investing in and carefully preparing strategies to remove adoption barriers.

4.4.4 Enhancing Traceability and Quality Control

All articles are central to improving the food supply chain's traceability and quality control. Real-time monitoring and data analysis are made possible by I4.0 technologies, which reduce food waste and increase product quality and safety [46,117].

4.4.5 Economic and Social Implications

The articles also discuss how implementing I4.0 technologies would affect society and the economy. Although these technologies have the potential to lower costs and increase market competitiveness, they also come with a high upfront cost and may cause resistance within the workforce since they alter job responsibilities and skill needs [52,115].

4.5 Description of Key Themes

4.5.1 Technological Advancements and Innovations

The expansion of advanced technology is constantly highlighted as a significant theme in the literature review. Industry 4.0 transforms the food business by introducing several innovations, including Additive manufacturing, Cyber-Physical Systems, Big Data, and loT. According to [117], blockchain and loT significantly improve food supply chains' traceability and transparency, resulting in more secure and productive operations. Studies by [46] describes how these technologies improve manufacturing and may provide a more responsive and integrated production environment.

4.5.2 Integration of Sustainability in Industry 4.0 Models

One central theme of Industry 4.0 is incorporating sustainable practices into corporate strategies. In studies by [52] authors explored how Industry 4.0 helps achieve the Sustainable Development Goals (SDGs) and supports sustainable business models. [115] pointed out that I4.0 concept can drastically cut waste and energy usage in food processing operations, bringing industrial practices into line with environmental sustainability objectives.

4.5.3 Challenges and Barriers in Implementation

A recurring theme in the literature is the many obstacles and difficulties associated with adopting I4.0 technologies. [114] pointed out several challenges, as complicated technology, expensive prices, and problems with data administration. These difficulties show that strategic methods are required to successfully resolve these obstacles and promote the adoption of I4.0.

4.5.4 Enhancing Traceability and Quality Control

Improving quality control and traceability with Industry 4.0 technologies is a significant theme. Both studies [46,117] highlights how these technologies play a part in delivering data analysis and real-time monitoring, which improves product quality safety and decreases food waste.

Figure 17. Initiatives for traceability can aid in lowering food fraud [120]

This demonstrates how I4.0 may be used to guarantee product integrity and customer trust and improve operational efficiency. Recent food fraud incidents in China, like the 2015 "zombie meat scandal" involving 100,000 tons of expired meat, have raised consumer concerns about food safety and validity. A recent report found that 71% of Chinese citizens view food safety as a significant issue, urging the government to enhance laws and impose severe sanctions on violators.

4.5.5 Economic and Social Implications

One important theme is the impact of Industry 4.0 adoption on the food industry from an economic and social standpoint. [52] discussed the financial advantages like increased market competitiveness and cost savings. Whereas [115] highlighted that introducing these technologies must be balanced and deliberate since they also come with a high cost and the potential to create opposition among the workforce owing to shifting job positions and skill needs.

4.6 Discussions

4.6.1 Changing Practices

Sustainability has been made considerably possible by the revolutionary changes in food sector production, distribution, and other practices brought about by adopting Industry 4.0 technologies. One significant development noted is the move toward more sustainable and effective production techniques. Blockchain and other loT technologies can improve food supply chains, traceability, and waste reduction, according to [46,117]. This production modification ensures food safety reduces environmental impact, and boosts resource efficiency. Nestle has advanced product development using I4.0 technologies. Since 2016, the corporation has developed 60% faster, tested, and launched 12% more technologies between 2020 and 2021. Nestle reimagines core 47 brands, optimizes its portfolio, and uses innovative approaches [121]. Technology has expanded business models and customer satisfaction for corporations. The Open Channel platform promotes internal crowdsourcing and innovation [121]. This method follows Industry 4.0 concepts of rapid, technology-driven development and customer relevance, which are essential for the food industry's sustainability. Distribution supply chains are more visible and integrated thanks to I4.0. Authors [52] noted that digital technology offers real-time food tracking and administration from farm to table. Ensuring the sustainability of food items throughout their lifecycle requires this level of transparency. Furthermore, intelligent warehousing and logistics development have been made possible by these technology breakthroughs, which have improved distribution efficiency and decreased carbon footprints, all supporting environmental sustainability.

4.6.2 Technology Adoption Trends

The theme analysis reveals essential trends in the food industry's adoption and application of Industry 4.0 technologies. The increasing integration of blockchain with loT technologies is a prominent trend, as [117] highlighted. Because of these technologies' capacity to improve supply chain traceability and transparency, which significantly advances sustainable practices, they are being increasingly implemented.

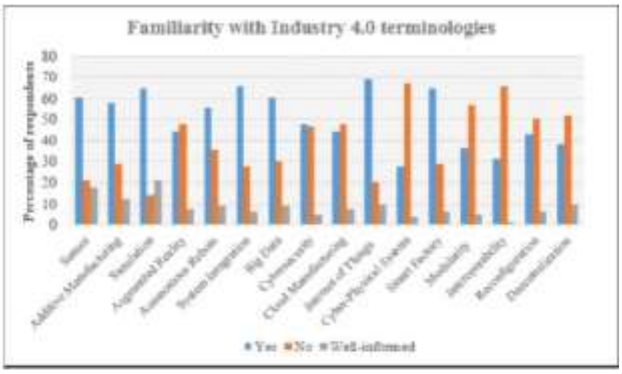

Figure 18. Familiarity with I4.0 Terms [122].

Another trend is employing big data analytics and Al to handle complex supply chain operations and predict market trends, according to [46]. These technologies enable food producers to reduce waste and maximize resource utilization while promptly responding to consumer needs and market shifts.

4.6.3 Sustainability Implications

The food industry's adoption of I4.0 carries significant consequences for sustainability, including economic, social, and environmental aspects. Economically, as the theme analysis clarifies, I4.0 technologies like loT and Big Data increase productivity and efficiency, dramatically lowering operating costs and waste [117]. Implementing these technologies reduces resource utilization and carbon emissions environmentally. Integrating Industry 4.0 technologies, especially in sustainability, shows PepsiCo's environmental responsibility. The company's pep+ (PepsiCo Positive) strategy transforms operations and innovation [123]. PepsiCo takes sustainability seriously by employing Al to detect factory water leaks and developing bio-based product displays. These activities, data-driven decision-making, and tech startup alliances demonstrate PepsiCo's commitment to Industry 4.0 for food industry sustainability. Blockchain and CPS increase food waste traceability and quality control, essential to environmental sustainability [46]. I4.0 technology can improve food quality and safety, boosting customer confidence and public health. However, it also brings up skill gaps and labour displacement issues, which makes workforce development and training essential [52].

4.7 Critical Analysis: SWOT Evaluation of Literature Findings

Strengths, Weaknesses, Opportunities, and Threats are the four main components that make up the acronym SWOT analysis. This strategic tool is used to identify opportunities and threats from the outside as well as internal strengths and weaknesses.

Table 4. SWOT Analysis of Industry 4.0 Technology Adoption in the Food Sector

Internal	
Strengths(S)	***Weaknesses (W)***
▪ Streamlining procedures to enhance quality assurance and minimise waste. ▪ Implemented efficient transportation routes and established refrigerated storage chains to minimise emissions. ▪ Potential for improving traceability and transparency with technologies like big data, blockchain, & IOT. ▪ The incorporation of sustainability and circular flows into business models.	▪ Adoption is constrained by high costs, particularly for smaller businesses. ▪ Lack of technical expertise and skills impeding implementation. ▪ Complex systemic integrations that limit implementation. ▪ Privacy ethics are at risk due to excessive data collection.
External	
Opportunities (O)	***Threats (T)***
▪ Efficiency enhancement by closely monitoring and optimising processes to minimise waste. ▪ Enhancing transparency to facilitate issue tracing and increase consumer trust. ▪ Intersectoral collaboration for knowledge sharing and promotion of best practises. ▪ Integrating sustainability and circularity into business models.	▪ Risks associated with cybersecurity are rising with hyper-connected systems. ▪ Insufficient progress in tailoring skills development to meet the demands of emerging technologies. ▪ The deployment of a system can be limited by the complexities associated with system integration.

SWOT analysis is a frequently used method for strategic planning. The method first developed by Albert Humphrey, a well-known researcher and the head of Stanford University's Team Action Model (TAM) research team in the 1960s and 1970s. The SWOT analysis provides a strategic perspective on the industry's ability and readiness to incorporate Industry 4.0 technologies, offering a summary. The analysis provides a detailed understanding of the organization's abilities and limitations by examining internal factors such as industry-specific strengths and weaknesses. It simultaneously analyses external factors, including opportunities and threats, to help identify potential areas for growth and challenges within the industry's environment [124-127]. The SWOT analysis, as presented in Table 4, identifies crucial factors related to technological potential, obstacles to adoption, enhancements in processes, and measures to mitigate risks. It consolidates findings on the promises of sustainability, economic considerations, societal impacts, and challenges in implementation.

4.8 Critical Reflection

When the findings are examined critically, it becomes clear that Industry 4.0 technologies have the potential to revolutionize the food sector, but there are obstacles to their adoption. The themes found indicate a dynamic interaction between sustainable behaviours and technology development. Although technologies like blockchain and the Internet of Things fuel innovations in transparency and efficiency, obstacles, including high implementation costs and opposition to change, highlight the need for well-rounded and calculated methods [114,115]. Furthermore, concerns concerning the accessibility and inclusivity of these technologies are brought up by the emphasis on process, product, and business model improvements, especially about smaller companies in the food industry. The review also identifies a significant research vacuum regarding these technologies' long-term sustainability effects and how they contribute to sustainability that is more general objectives, such as the SDGs.

Therefore, even while I4.0 offers a route to a more sustainable food, a thorough grasp of its effects on the economy, society, and environment is required to realize its promise fully. Therefore, the critical role that I4.0 technologies play in promoting sustainable innovation in the food sector been clarified by this research. Together, the theme analysis, critical debate, literature review highlights how these technologies have the power to improve environmental stewardship, industrial efficiency, and traceability significantly. Adopting I4.0 represents a critical advancement in the development of the food industry, not only in line with operational and commercial aims but also in terms of more significant environmental and social sustainability objectives.

4.9 Conceptual Framework

Implementing I4.0 in food manufacturing industry should consider a conceptual model that highlights necessary obstacles and crucial success factors as shown in figure 19.

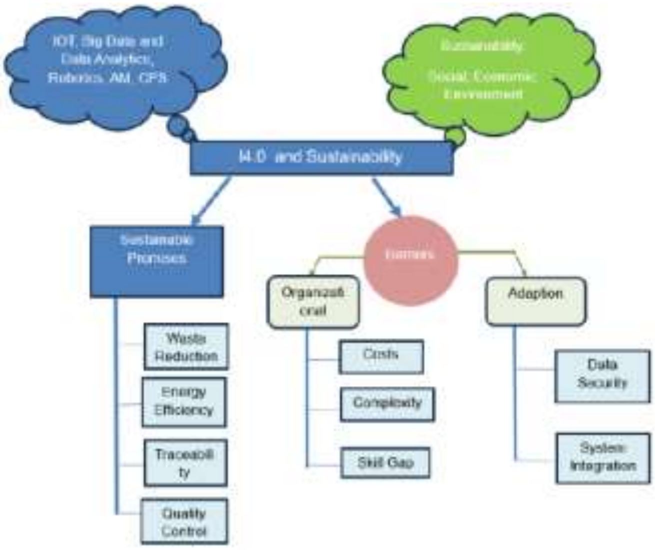

Figure 19 Conceptual Framework for 14.0 and Sustainability

The model is based on a thorough review of academic literature and a thematic analysis of secondary data. To address sustainability goals like transparent traceability, optimised waste reduction, and monitored energy efficiency, food producers can make use of foundational 14.0 technologies, such as advanced robotics and Internet of Things sensors. The model also reveals real adoption barriers that could be carefully addressed during implementation of 14.0 technologies. Operational development is slowed down by additional expenses, supply chain integration's operational complexity, and internal skill gaps in data and digitization.

5. Conclusion Limitation and Future Directions

The research showed huge potential of emerging technologies to advance food system sustainability, particularly Additive manufacturing, robotics, Internet of Things (loT), and predictive analytics. These have potential to significantly increase food manufacturing transparency, product traceability, resource efficiency, and waste reduction while tackling urgent global issues like food scarcity and climate change. Research measured currently underutilised potential of certain technologies, such as digital twin (block-chain, loT), with applications for reliable monitoring, consumer trust-building, and verification that are currently ignored in food industry. Furthermore, analysis highlighted potential benefits for process optimisation, cost reduction, new revenue streams, and overall environmental gains that can arise from companies strategically investing in integration of analytics, automation, and smart connected systems throughout value chains. This validates the extensive financial and ecological advantages for digitally revolutionising traditional food production networks, with technologies advanced enough to be widely accepted. Study also identified significant barriers that presently stand in way with implementation of I4.0 systems for sustainability. It is important to address issues with process standardisation, high upfront costs, cultural resistance, and skill gaps in the workforce of the food industry. Notably, food companies are forced to adopt these cutting-edge technologies regardless of their flexible operations by accelerating policy measures, investor pressure, and shifting consumer demands for foods sourced ethically and sustainably.

Objective 1: Explore applications and potential advantages of main Industry 4.0 technologies being used in food industry today.
Achieved by a thorough analysis based on most significant findings regarding enormous potentials of blockchain, advanced robotics, Internet of Things sensors, and predictive analytics for facilitating transparency, traceability, resource optimisation, and waste reductions in the food production and supply chains. These capabilities directly address the critical sustainability issues that world's food systems are currently facing, such as reducing greenhouse gas emissions, use of chemicals, water waste, and food loss while advancing use of renewable energy sources, circular resource flows, and ethical sourcing.

Objective 2: Examine how Industry 4.0 technologies, with a focus on resource efficiency, waste reduction, and environmental impact that promotes sustainability in food production.
Identifying how cutting-edge I4.0 technologies can promote greater sustainability in second research objective. The application of I4.0 technology to create blockchain traceability platforms that provides unprecedented transparency directly relates to fundamental concept of maximising potential of technological integration opportunities to confirm ethical source of products, their sustainability credentials, and to enable circular resource flows in line with research themes. On the other hand, goal of qualifying mechanisms for reducing waste, resource depletion, and environmental footprints during food

production and distribution is fulfilled by potential of loT systems, intelligent robotics, and predictive analytics to optimise transportation emissions, refrigeration-heating energy uses, and model plan distributions.

Objective 3 - Consider economic, environmental, and social factors as you evaluate the opportunities and challenges of implementing I4.0 technologies for sustainable innovation in the food industry.
Through a balanced analysis of financial incentives like new revenue streams, competitive differentiation, and cost savings against obstacles around technical integration, standardisation, skill gaps, and security needs, goal of evaluating linked opportunities and challenges was effectively fulfilled. Furthermore, implications discussed ranged from promoting policy partnerships that are essential for infrastructure readiness to building customer trust by addressing counterfeit concerns.

Research represents a fundamental contribution to advancing digitalization for global transformation of food sector by thoroughly assessing Industry 4.0's sustainability benefits along with significant practical applications within current food manufacturing environments. Provided that these technologies are implemented with purpose, they can mitigate a wide range of sustainability challenges, from soil depletion and ethical sourcing to food waste as well as greenhouse gas emissions.

A major limitation of this study is its limited temporal scope, as research was restricted to a specific timeframe. This constraint hampers thorough investigation of dynamic nature of Industry 4.0 applications in food manufacturing industry over a long period of time. Due to time limitations, only secondary data review was used, and primary data collection methods were not included. This constraint impedes achievement of deeper and more transformative empirical insights into research phenomenon. The availability of comprehensive and standardized metrics related to adoption of Industry 4.0 in food manufacturing industry is limited. Data accuracy and comparability may be affected by differences in reporting and measurement practices among various sources.

A thorough assessment of potential in Industry 4.0 technologies promotes sustainability in food systems. However, continuous advancements in areas such as artificial intelligence, blockchain, and robotics offer plenty of opportunities for further investigation as their adoption progresses. According to the analysis, there is general agreement that more research is necessary, especially in areas like marketing innovations, organizational and open innovations, and the impact of these technologies on long-term sustainability [52, 114]. Studies underscore the need to investigate these promising domains, highlighting the continuous progression and possibilities of Industry 4.0 within food sector [114]. Due to depletion of numerous traditional biological resources for food production worldwide, there is a growing demand from consumers for healthier and more sustainable products. This has led to an increased necessity for alternative food resources [43]. (2022). Emerging products derived from cultured meat, meat alternatives, plant-based proteins, insect-based proteins, and similar sources have demonstrated considerable promise. The utilization of raw materials and emerging technologies can serve as valuable assets in the creation of highly accurate personalized nutrition recommendations [43]. Furthermore, they can also promote favourable consumer behaviour and promote a wider range of consumption patterns, ultimately resulting in improved health and enhanced food sustainability.

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