PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.8019

eISSN 2348-1900

REVIEW ARTICLE

Constraints, opportunities and future strategic solutions of fourth industrial revolution technologies in smart agriculture: A systematic review for Bangladesh

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Received: 01 March 2025; Accepted: 14 June 2025; Available online: Version 1.0: 21 August 2025

Cite this article: Sarker UK, Ahmed MT, Upama SA, Saha G, Uddin MR. Constraints, opportunities and future strategic solutions of fourth industrial revolution technologies in smart agriculture: A systematic review for Bangladesh. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.8019

Abstract

In the current period, the term Industry 4.0 or Fourth Industrial Revolution is a commonly used slogan that signifies the adoption of troublesome digital technologies (such as autonomous robots, cloud computing, Internet of Things, 3D printing, big data, augmented reality, smart sensors, cyber-physical system, biotechnology, drones, virtual reality, artificial intelligence, etc.) in the construction procedure which is transforming the trade units into keen factories and facing a great alteration in the worldwide value chain. Additionally, these innovative digital technologies have a significant impact on economic growth, globalization, international trade, government policies, global supply chains and the evolution of human capital. This review study aimed to assess the impacts, challenges and opportunities of the Fourth Industrial Revolution, with a specific and broad focus on Bangladesh. The findings indicated that, despite its substantial potential, the adoption of Industry 4.0 technologies in Bangladesh faces several challenges, including a lack of awareness, insufficient capital, inadequate infrastructure, a shortage of skilled professionals and various socio-economic issues. This review paper establishes conceptual links between strategic planning and the implementation of critical Industry 4.0 technologies, aiding in formulating future policy guidelines concerning the opportunities, implementation and strategic decisions related to the Fourth Industrial Revolution in Bangladesh.

Keywords: artificial intelligence; challenges and opportunities; industry 4.0; internet of things; machine learning; smart innovation; strategic solutions

Introduction

Global food insecurity is projected to intensify due to various factors including pandemics such as COVID-19, extreme climate events like floods and droughts and conflicts that disrupt food supply chains. These issues are compounded by rapid population growth, which significantly challenges increasing food production while maintaining environmental standards, human health and food quality (1, 2). Additionally, current food systems contribute significantly to climate change and produce substantial waste, making them unsustainable (3, 4). Therefore, adopting sustainable food practices is critical for achieving the United Nations' Sustainable Development Goals (SDGs) by 2030, though the COVID-19 pandemic has hindered progress (5, 6). Immediate innovative solutions and significant transformations are essential to support current and future generations (7). At least 11 of the 17 SDGs established by the United Nations in 2015 are closely linked to the food system. Redefining the structure and governance of food systems is essential for achieving "No poverty" and "Zero hunger". These goals are closely tied to agricultural and food industry practices, primarily through green food processing techniques. The Asia-Pacific region has witnessed rapid economic expansion with GDP growth rates between 6 % and 8 % over the past two decades. Export earnings have increased by approximately 10 % annually, positioning Bangladesh as the world's twenty-eighth largest economy by 2030 (8-10). In the fiscal year 2018-19, agriculture, industry and services contributed 13.32 %, 31.15 % and 55.53 % to the GDP respectively, with approximately 85 % of export earnings generated by the Ready-Made Garments (RMG) sector (11, 12). Despite global challenges, Bangladesh has maintained robust growth, controlled inflation and stabilized its GDP through sound macroeconomic policies and structural reforms (8). However, to fully leverage the transformative potential of Industry 4.0, Bangladesh must adapt and implement its technologies in manufacturing and services (13). The IT industry is not only central but also a driving force behind Bangladesh's digital transformation and economic growth, with technology product exports expected to reach $5 billion by 2025, up from approximately $1 billion annually. Over 8000 digital centres have been established nationwide to provide various digital services (8, 13, 14). Industry 4.0 offers opportunities and a promising future for companies to enhance production and stimulate economic growth (15, 16).

Numerous studies have indicated that the Fourth Industrial Revolution, commonly referred to as Industry 4.0, introduces innovative approaches to addressing global challenges, including food quality (17) and food traceability (18). Although there is no universally accepted definition for Industry 4.0 (19, 20), within the agri-food sector it is commonly associated with a suite of advanced technologies such as the Internet of Things (IoT), big data, cloud computing, artificial intelligence (AI), 3D printing, intelligent sensors, blockchain, digital twins and robotics (17, 21-23).

Recent literature reviews emphasized the convergence of Industry 4.0 technologies and sustainable development. Studies have explored how technologies associated with Industry 4.0 enhance lean manufacturing and support sustained organizational performance (24). Additionally, the influence of digital technologies on fulfilling the SDGs has been examined through a cross-case analysis of Italian agri-food companies (25). Numerous issues affecting the success of the green revolution and sustainable food systems have also been identified, along with proposed technology-based innovations to address these challenges (7). The relationship between agri-food 4.0 and sustainability is further highlighted by big data's role in valorizing agricultural waste (25) as well as recent developments in IoT applications for sustainable agriculture (26). It was argued that sustainability should be a core component of Industry 4.0 implementations to effectively support sustainable development (27). However, there is a significant need for comprehensive reviews that evaluate the impact of green technologies and Industry 4.0 innovations on the food and agriculture sectors. This article explores the role of Industry 4.0 and green technologies in propelling the global transition toward sustainable food systems in Bangladesh.

Methodology

A methodical review method was used to collect relevant literature and research studies on the level of incorporation of Fourth Industrial Revolution (4IR) technologies. The PRISMA approach was used in this study followed by well-defined steps (Fig. 1) (28, 29). Numerous academic databases, including Science Direct, PubMed, Google Scholar, IEEE Xplore and Web of Science were investigated for pertinent research articles published in the previous decade. The literature search was accomplished between 15th to 30th May 2024. Keywords used for the search comprised "Smart Technologies", "Fourth Industrial Revolution", "Internet of Things", "Artificial Intelligence", "Big Data", "Blockchain", "Machine Learning" and "Drone Technology". The insertion standards were based on the PICO framework (population, intervention, comparison, outcome), as summarized in Table 1 (30). Only articles relevant to 4IR technologies and smart innovation were incorporated. As an elimination principle, individual open-access articles available in English within the past period were considered.

The initial search yielded 973 studies; however, based on the exclusion criteria, a total of 82 documents were considered acceptable, hence nominated for this review. The selected articles were systematically reviewed and studied to extract main material related to the application of 4IR technologies in developing countries including Bangladesh. The data extraction procedure involved evidence on the exact technologies used, their applications, results and challenges. The extracted data were produced and prepared thematically for individual technology. The previous portion of this document displayed the consequences and discourse resulting from the investigation of literature.

Table 1. PICO framework

Aspect	Criteria
P: Population	4IR smart innovation
I: Intervention	4IR technologies in smart irrigation
C: Comparison	This included various technologies like IoT sensors, data analytics, automation, that fall under the 4IR paradigm and are applied to smart irrigation systems. Studies that might have used traditional irrigation methods without 4IR technologies and do a comparison
O: Outcome	Constraints, opportunities and prospects of leveraging 4IR technologies for smart irrigation in Sub-Saharan Africa

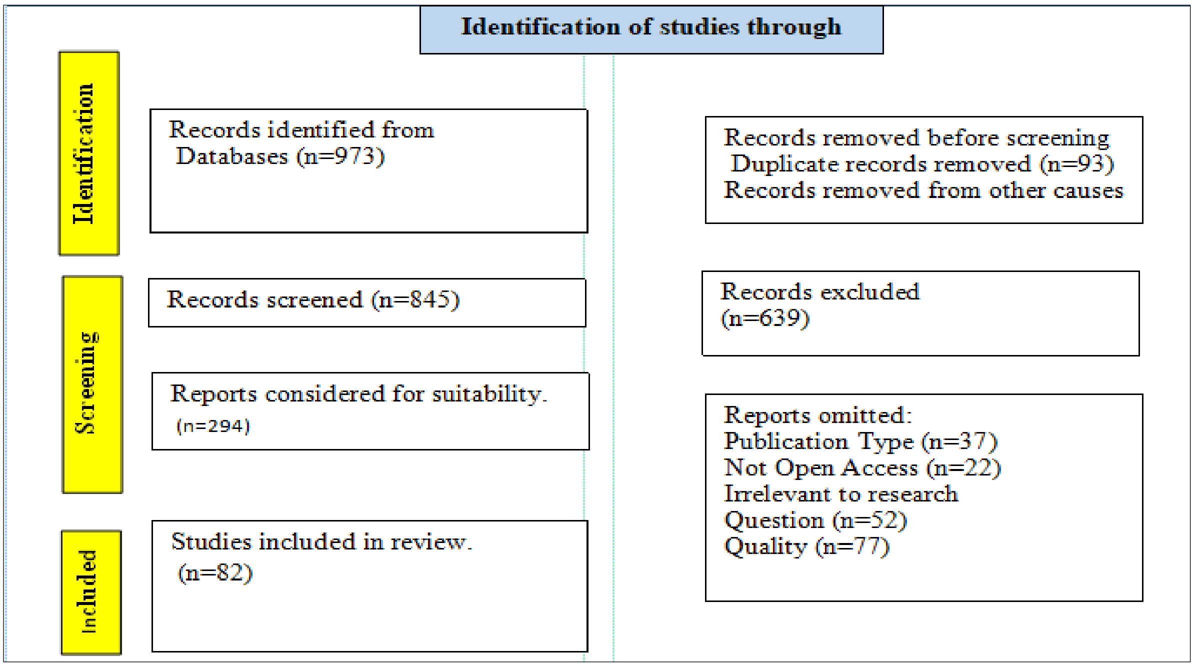

Fig. 1. PRISMA flow chart of literature screening and selection process (28).

Evolution of industrial revolution in the world

The First Industrial Revolution, also known as Industry 1.0, marks a fundamental milestone in the annals of human development, profoundly influencing modern history. This era, from 1760 to as late as 1840, was characterized by a significant shift from traditional manual production methods to more sophisticated machines powered by steam and hydropower. The transformation was most notable in Europe and the United States, where it took decades for the full effects of these technological innovations to permeate (31-34). The mechanization of production during this period was especially pronounced in the textile industry, which became the vanguard of industrialization. This revolution also catalyzed the growth of the iron and steel industries and chemical manufacturing and significantly enhanced agricultural and mining capabilities. Concurrently, there was a notable enhancement in transportation systems, which facilitated more efficient movement of goods and raw materials, critically supporting the burgeoning industrial activities (34-37). Economically and politically, England emerged as a dominant force during the mid-18th century, leveraging its advanced industrial capabilities to establish and control a vast trading empire. This empire extended across North America and the Caribbean and exerted substantial political influence in Bengal through its trading companies, reflecting a period of significant British colonial and economic expansion (31, 38-40). The socio-economic impact of the First Industrial Revolution was profound and multifaceted, marking a pivotal turning point in global socio-economic history. It opened new frontiers for further improvements in almost every aspect of daily life and societal structure (34, 41). However, the revolution also had its downsides, which included severe social issues such as the exploitation of child and women labourers, inhumane working conditions spanning up to sixteen hours a day and a generally unhygienic working environment. These factors contributed to a widening economic disparity between the wealthy and the poor, underscoring the complex legacy of this transformative period (34, 42).

The Second Industrial Revolution, often referred to as Industry 2.0, the Technological Revolution, or the American Technological Revolution, unfolded between 1870 and the onset of World War I in 1914. This era marked a significant evolution in the industrial landscape, characterized by rapid technological advancements and widespread innovations that reshaped manufacturing and production processes across the globe (43-45). This period was distinguished by introducing and integrating groundbreaking technologies, notably electricity, which revolutionized factory operations and the energy landscape. Other significant inventions included the telegraph, which transformed communications; medicinal advancements that improved public health; the combustion engine, which powered the new automobiles and aircraft and the development of marine ships that enhanced overseas transportation. Additionally, the era saw advancements in materials such as paper and rubber, which were critical for industrial and consumer applications. The chemical and petroleum industries also expanded significantly, supporting many other sectors, including the production of medical instruments and advancements in metallurgy within the iron and steel industries (43, 45, 46). The expansion of the railway network during this time dramatically improved transportation infrastructure, facilitating the more efficient movement of goods and people. This period also witnessed significant changes in education and the scientific management of manufacturing industries, which helped optimize production processes and work-force efficiency. The widespread electrification of factories and the adoption of these new technologies spurred substantial industrial development not only in traditional powerhouses like the Great Britain and United States but also in China, France, Japan, Germany and Italy. The extensive industrial growth during the Second Industrial Revolution profoundly impacted the global economy and people's livelihoods worldwide, setting the foundation for the modern, globalized economic structure we know today (46, 47).

The Third Industrial Revolution, which commenced in the 1960s, represents a significant shift in industrial development trajectory, influenced mainly by the aftermath of two world wars. This era, also widely recognized as the Digital Revolution or the Computer and Information Technology Revolution, heralded a new age of technology characterized by the integration of computing and digital communications technologies (48, 49). Central to this revolution was the development and widespread adoption of information technologies, including the internet, which unprecedentedly interconnected disparate regions and industries. Renewable energy sources such as wind and solar also began to play a crucial role, reflecting a shift towards more sustainable forms of energy production. The era was marked by significant advancements in computing hardware, from establishing mainframe systems to introducing personal computers and microprocessors, dramatically enhancing data processing capabilities and accessibility (50, 51). Additionally, the revolution introduced new digital manufacturing technologies, most notably 3D printing. This innovation allowed rapid prototyping and production, revolutionizing several sectors by enabling more flexible and cost-effective manufacturing processes. The impact of the Third Industrial Revolution was global, with profound effects not only in Western nations like the United States (US) and across the European Union but also in rapidly industrializing countries such as Japan and China. These technologies facilitated a new level of global integration, enhancing communication, trade and cooperation across international borders (48, 50, 52).

Industry 4.0, known as the Fourth Industrial Revolution, emerged prominently in 2011. The German government first introduced this concept as a high-tech strategy aimed at advancing the computerization of manufacturing. In the same year, the term "Industry 4.0" was officially introduced to the broader public during the Hannover Bureau of Industry Exhibitions, marking a pivotal moment in the evolution of industrial technologies (35, 53, 54). This revolution is characterized by integrating and adopting disruptive technological tools and cyber-physical systems, representing a significant departure from the Third Industrial Revolution. Industry 4.0 encompasses a wide range of technologies, including advanced robotics, AI, autonomous vehicles, IoT, materials science, biotechnology, big data analytics, energy storage, 3D printing, nanotechnology, quantum computing, innovative materials like graphene and financial technology (Fintech). These technologies are integral to this revolution, as they enhance the capacity to collect, analyze and transmit digital information across platforms (44, 55-57). Industry 4.0 revolutionizes the production landscape by leveraging integrated physical and cyber-physical systems to automate and customize mass manufacturing. This automation extends to the production of tailored products and services designed to meet the specific demands of modern-day consumers. The sophistication of these systems allows for greater efficiency and flexibility in manufacturing processes, enabling companies to respond quickly to market changes and consumer needs (58-62). Moreover, Industry 4.0 fosters a unique integration between digital and physical technologies, predominantly focusing on the innovative factory concept. This concept emphasizes a seamless man-machine interaction where smart factories are equipped with sensors, actuators and autonomous systems that communicate with each other and human operators. This integration facilitates a more efficient, adaptable and streamlined production process, which is fundamental to the future of manufacturing (49, 58, 60, 61). An illustrative overview of the industrial revolutions is depicted in Fig. 2.

Enablers and drivers of Industry 4.0 revolution

The Fourth Industrial Revolution or Industry 4.0 is propelled by various disruptive technologies, including the big data, cloud computing, AI, internet, autonomous vehicles, advanced robotics, and innovative materials. It also incorporates various manufacturing methods such as 3D printing and hybrid manufacturing, along with advancements in genetic and synthetic microbiology (44, 58). These technologies enable "smart industries" to integrate machinery and materials into industrial processes, enhancing capabilities and enabling greater personalization through digital and integrated methodologies (64). Industry 4.0 transcends traditional production and distribution methods, encompassing the entire value chain and fostering new product development (60, 65). Big data is pivotal in Industry 4.0, aiding in the collection, processing and analysis of vast, unstructured datasets with the help of intelligent algorithms that enhance decision-making processes (58, 60, 62, 65, 66). Cloud computing plays a critical role by managing large data volumes on open systems and offering real-time connectivity to production systems, thus enabling global access to information and increasing operational flexibility (62, 66, 67). In smart factories, the digital transmission of data necessitates robust cyber security measures to safeguard industrial information (58, 68, 69).

Industry 4.0 signifies a transformative phase in manufacturing, driven by technological advancements and prominently featuring automated and advanced robotics. These robotic systems are not standalone; rather, they are intricately linked and managed within intelligent factories, integrating seamlessly with corporate systems to enhance operational efficiency and responsiveness (65). This era is also marked by the rise of disruptive technologies that cater to the increasingly personalized demands of consumers, leading to significant developments in additive manufacturing and 3D printing technologies (60). Furthermore, Industry 4.0 enables both vertical and horizontal integration of technologies. This integration facilitates cross-group corporate data sharing and interoperability according to established data transfer standards, enhancing organizational agility and data-driven decision-making (59, 60, 61, 70). The benefits of this new industrial revolution are manifold. They include shortened timeframes for launching new products, more adaptable production lines, improved productivity, efficient resource utilization and enhanced capabilities for companies to integrate into global value chains (64, 71).

Moreover, Industry 4.0 facilitates the flexible customization of production chains by enabling direct communication among various components through flexible automation systems. This advancement not only improves the production efficiency but also supports the production of large-scale and bespoke manufacturing demands effectively (71, 72).

Global impact of the Industry 4.0

The Fourth Industrial Revolution, a transformative epoch in human history is driven by significant technological breakthroughs that build upon the foundations of the previous three industrial revolutions (44, 73, 74). We are currently in the

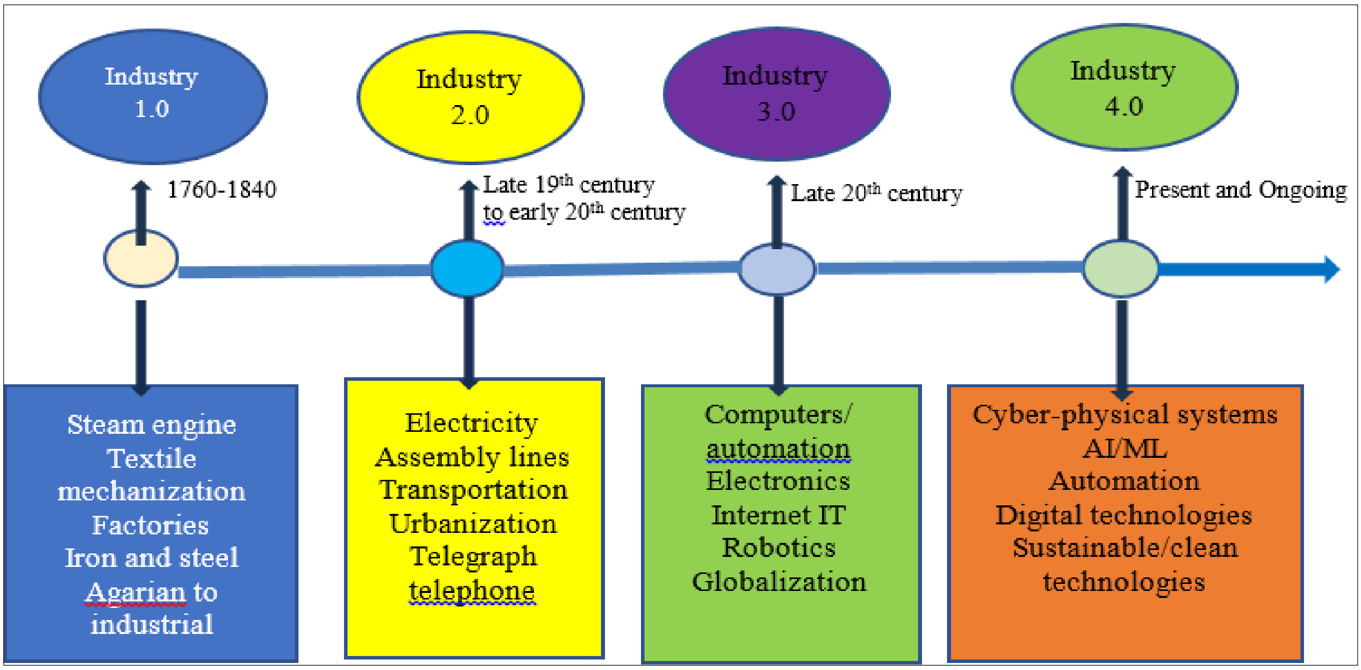

Fig. 2. The industrial revolution (63).

midst of a paradigm shift where Industry 4.0 is revolutionizing manufacturing and extending its influence across various sectors, including the economy, international trade, globalization, governance, society, individual lifestyles, information access, global supply chains, bio-research and human capital development (48, 75-78). Industry 4.0 is facilitating a significant transition from traditional analog and mechanical processes to intelligent, digital production facilities that support virtual and customized products, along with innovative operational models (48, 55, 61, 79, 80). Revolutionary digital technologies are reshaping societies and the global economy in a sophisticated and integrated manner (81, 82). The Fourth Industrial Revolution, with its anticipated substantial improvements in productivity, economic growth and development through cutting-edge and disruptive smart technologies, holds the promise of enhancing productivity and promoting economic expansion (48, 83, 84). It is poised to profoundly transform the global labour market by creating new job opportunities and altering necessary job skills and employment conditions. Traditional roles, particularly those involving repetitive tasks, are expected to be replaced by positions requiring new skills, leading to the automation of many manual processes (48, 78, 85, 86). Key technologies linked to the Fourth Industrial Revolution, such as big data, IoT, autonomous robots, cloud computing, virtual and augmented reality, fintech, AI, 3D printing, intelligent sensors, cyber-physical systems, simulation, drones, nanotechnology and biotechnology are profoundly influencing our daily routines, communications and lifestyle (44, 87-89). This transformative era is also reshaping various aspects of society, such as governance, education, healthcare and international trade, influencing nearly every aspect of modern life.

Current prospects of Industry 4.0 in developing countries

According to the framework provided by the Boston Consulting Group, Industry 4.0 will significantly reduce human physical effort and decrease the need for face-to-face meetings in management-level decision-making. This new industrial paradigm is frequently described as a manufacturing revolution, termed the “Manufacturing Renaissance” in the United States and “Made in China 2025” in China (90, 91).

Germany stands as a beacon of progress in implementing Industry 4.0, with German experts estimating their progress at an impressive level of 3.8. Ultimately, they are poised to adopt Industry 4.0 within the next decade. The transition from Industry 3.0 to 4.0 is a journey of incremental steps. While Industry 4.0 has firmly taken root in some Western countries, it remains a novel concept for decision-makers and planners worldwide (92, 93). However, the potential of Industry 4.0 is undeniable, especially for nations heavily reliant on manufacturing and those experiencing rapid economic growth.

Countries newly engaging with the industrial sector face structural challenges and confusion regarding Industry 4.0, which hampers the adoption and application of its technologies (94-99). Developing countries such as Indonesia, India, Brazil, Pakistan, Nigeria, Thailand and Malaysia are actively pursuing the adoption of Industry 4.0. These nations invest in technologies that meld human efforts with enhanced production capabilities (100-103). Despite these initiatives, empirical research on the potential of Industry 4.0 in Bangladesh remains sparse, even though the country is expected to become the world's twenty-eighth largest economy by 2030.

Industry 4.0 in Bangladesh perspective

The Asia-Pacific region is one of the fastest-growing economies worldwide, achieving GDP growth rates of 6 % to 8 % over the past two decades. Export earnings have consistently risen, averaging around 10 % annually, despite some variations and it is projected that Bangladesh will become the twenty-eighth largest economy by 2030 (8-10). Agriculture remains a vital component of the economy, contributing approximately 13.32 % to GDP and employing 43 % of the workforce as of FY 2022-23 (104). The agricultural sector is critical for food security and poverty reduction despite its traditional reliance. However, it faces issues like climate change, limited crop diversity, resource degradation and the use of harmful agrochemicals. Recently, the adoption of Industry 4.0 technologies such as digital machinery, AI in farming, IoT devices, big data and software modules has opened new possibilities for enhancing food security in Bangladesh (105, 106). The onset of the Fourth Industrial Revolution has driven extensive industrial automation in various sectors in Bangladesh, including RMG, textiles, agro-processing, furniture, footwear, leather, tourism and hospitality. The RMG and textile industries significantly bolster the export income (about 82 %), GDP (14.07 %) and employment (4 million workers). The RMG sector is increasingly adopting automation technologies to maintain productivity and competitiveness, albeit with potential job losses for low-wage workers. Other industries also invest in automated machinery, robotics, sensors, IoT and big data to improve manufacturing efficiency and business management. A McKinsey report predicted that automation will result in a loss of 5.7 million jobs, primarily among unskilled workers in the coming decades. In Bangladesh, approximately 90 % of industrial units are small and medium-sized enterprises (SMEs) using technologies from the first, second and third industrial revolutions. Despite the potential benefits of adopting Industry 4.0, several challenges must be addressed, including limited awareness, insufficient labour skills, inadequate factory infrastructure, restricted investment and underdeveloped technology applications (107, 108). Bangladesh is often critiqued for its limited production capabilities, low labour skills, poor infrastructure and weak technology application (107, 108). The country faces significant obstacles such as inadequate infrastructure, insufficient government support, dependency on cheap labour, human reliance on manufacturing, high costs of technological installations and health and safety concerns (8, 15, 107-109).

Overview of Industry 4.0 technologies

Industry 4.0 is transforming various sectors and improving food supply chains with cutting-edge computing networks fueled by advancements in IoT, AI, blockchain, robotics, big data analytics and communication technologies like 5G (110, 111). An extensive array of sensors, systems, devices, machines, factories, animals, crops, farms and individuals continuously produce data within these supply chains. This data promotes sustainable development (112, 113). The application of Fourth Industrial Revolution technologies in innovation (Fig. 3) signifies a significant rise advancing in recent agriculture.

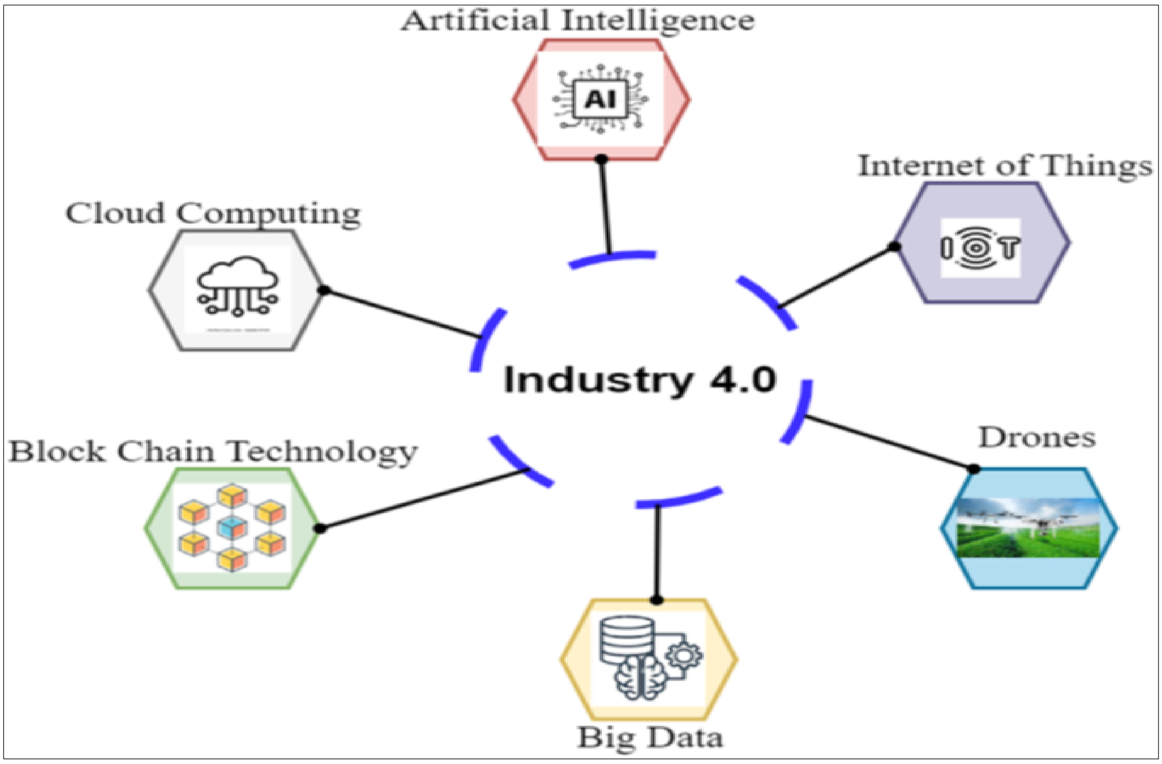

Fig. 3. Industry 4.0 technologies for smart innovation.

Artificial intelligence

Understanding the complexity of the food system, which interacts closely with economic, environmental and societal factors, is crucial for developing sustainable strategies that ensure adequate, safe and nutritious food. The intricate dynamics of today's food supply chain necessitate a systems approach to address the impacts at each stage thoroughly. Recent research has demonstrated the effectiveness of this approach, using AI as a powerful tool to enhance food safety and prevent fraud (114–117). These studies have employed expert elicitation and Bayesian Networks, consistently achieving prediction accuracy often above 90 %, providing a reassuring solution to food safety challenges. AI manages the entire process to enhance transparency and traceability within the food supply chain, refining aspects like production operations, inventory management, price forecasting, logistics and cost analysis (118, 119). AI improves production systems and intelligent logistics by leveraging data from diverse sources such as sensors, cameras and internet connectivity. This integration is crucial in monitoring crops and vegetables, substantially minimizing waste (120, 121). AI also boosts efficiency and precision, especially in repetitive tasks within manufacturing and agriculture such as precisely sorting potatoes suitable for chips versus those for French fries (112, 122). Furthermore, AI addresses complex issues in livestock farming and the broader food industry (123).

Big data technology

Big data technology plays a crucial role in the food supply chain, where intelligent machines, cameras, sensors and other devices continuously generate vast amounts of data. With improvements in computational power and technology, processing this data has become increasingly efficient. However, handling the vast amounts of big data produced throughout the food supply chain remains a challenging and time-consuming task, demanding substantial computational resources. Although cloud computing technologies have been effectively implemented in various sectors, their integration into the food supply chain is still progressing (124, 125). It is crucial to address multiple research challenges including availability, data integrity, data governance, privacy, scalability, data transformation and legal issues. Cloud computing, with its ability to facilitate a "lab to sample approach" is a powerful tool for enhancing food safety. It facilitates the on-site collection of food safety data using portable devices and sensors, which is then transmitted to a centralized cloud-based infrastructure for processing and analysis. The results are promptly communicated back to the operator on-site, aiding in decisions regarding food safety compliance. This process reduces costs by ensuring that only suspected samples undergo further laboratory testing by skilled personnel using advanced equipment. Moreover, IoT technology, when integrated with cloud computing can detect potential food safety risks early, enabling timely interventions to mitigate these risks (113, 123, 125).

Internet of things and smart sensors

The food supply chain is ideally suited for IoT solutions because it needs continuous monitoring and control across vast areas. IoT enables data collection at every stage of the food supply chain through advanced sensors and devices that monitor quality, temperature, machine maintenance, storage, transportation and environmental information in real time throughout a food product's lifecycle (113, 117). In the food sector, IoT applications provide extensive traceability options, allowing tracking of product locations, production and delivery schedules, sources of ingredients and handling and usage histories. Moreover, IoT sensors are crucial for temperature monitoring at critical points within cold food supply chains. A broad array of spectroscopic methods across near-infrared (NIR), visible (VIS), ultraviolet (UV) and mid-infrared (MIR) spectra has been thoroughly studied, with the VIS-NIR spectrum being most frequently utilized for food product analysis. These techniques are expanding beyond lab settings to field applications and consumer usage, propelled by the swift development of smartphone applications. These apps help analyze various factors, including chemical composition, colour, microplastic detection, microbial spoilage, authenticity and process monitoring (126, 127). Additionally, intelligent sensors using hyperspectral imaging (HSI) are gaining prominence in the food industry for their ability to rapidly deliver spatial and spectral information without requiring solvents or extensive training. Consequently, HSI is viewed as a pivotal technology in advancing Industry 4.0, generating enthusiasm for the potential applications of these techniques (23, 128).

Robotics and smart machines

Automation and robotics are central components of the industry 4.0 framework, serving critical roles in various sectors. This involves deploying robots, automated control systems and AI across all production phases in agriculture. In the food industry, intelligent factories adopt sophisticated automation technologies and utilize autonomous robots (3, 112, 113). Intelligent machines in agriculture handle tasks such as cultivation, sowing, transplanting, feeding, fertilizing, picking, spraying, irrigating and harvesting. These machines also gather essential data on soil, water quality, crops and aquatic products, facilitating precision agriculture (129). Similarly, in food manufacturing and post-harvest supply chains, processes like sorting, packing, shipping, quality control, picking and distribution are increasingly automated with robotics (130, 131).

Digital twins

Digital twins, virtual models derived from simulations, are increasingly used to assess performance parameters, enhance processes, add value and support sustainable manufacturing operations (132). In smart farming, digital twins enhance productivity and sustainability by optimizing farming techniques (133). Additionally, they tailor supply chains and predict the quality of food post-harvest, which helps extend shelf life and reduce food wastage (134). Benefits of digital twins include minimized product variability, reduced resource use, energy conservation, improved production scheduling, better logistics and enhanced transparency. However, the implementation of digital twins is limited by the need for interdisciplinary approaches and specialized skills in modeling and programming (135).

Issues, challenges, opportunities and strategic solutions

The disruptive technologies of the Fourth Industrial Revolution are reshaping various aspects of life such as production, the economy, business, governance, society and cultural exchanges, while also giving rise to new challenges. Bangladesh on the rise, progressively embraces these revolutionary technologies across various sectors to foster socio-economic development. However, this region faced obstacles, including limited awareness, insufficient funding, the availability of cheap labour, inadequate digital infrastructure, skill shortages and socio-economic issues. In response, both public and private sectors have recently initiated efforts to enhance infrastructure and build human, technical and financial capacities. These efforts aim to improve education and training systems to capitalize on the opportunities presented by the 4IR. This study evaluates practical outcomes to pinpoint challenges and opportunities and it proposes strategic solutions offered by Industry 4.0, with a specific focus on Bangladesh.

Awareness building

The concept of the 4IR is relatively new, underscoring the need to enhance awareness among diverse stakeholders such as authorities, policymakers, businesses, industries, academics, employees and consumers. Boosting understanding among authorities and policymakers can catalyze economic growth and development. It can boost business and industries' productivity, flexibility, efficiency and competitiveness. Within academia and among employees, it fosters the creation of high -skilled and well-paid jobs and for consumers, it enhances satisfaction and product customization. The familiarity with Industry 4.0 technologies in Bangladesh is limited, yet it is crucial for propelling economic advancement and achieving international standards (13). Workers, SMEs, industries and national economies frequently need more awareness and resources to transition to Industry 4.0, posing a stagnation risk. Policymakers and advocates must launch awareness programs such as seminars, trade fairs and international training opportunities for all parties involved.

Capital formation

Financial investment is essential, as the development, transformation and implementation of digital technologies require substantial funding across various sectors. Industry 4.0 demands significant capital to construct smart economic infrastructures and adopt intelligent business models. However, the banking sector has been reluctant to finance high-tech industries, citing high risks and the novelty of these sectors as significant concerns. Additionally, the availability of inexpensive labour often deters Bangladesh's entrepreneurs from investing in automation. Considering that over 90 % of businesses in Bangladesh are micro, small and medium enterprises, accessing substantial capital for innovative technology presents a significant hurdle. The government ought to implement incentives that motivate the banking sector to provide financial support for high-technology industries in Bangladesh.

Socio-economic challenges

The 4IR is marked by the fusion of digitization and automation, which enhances machine intelligence, interactivity and user-friendliness. These advancements will significantly transform work patterns by introducing new robots capable of interacting with humans. This technology will augment human cognitive abilities and synergize with other emerging technologies to develop innovative computational models. Addressing challenges is crucial particularly bridging the gap between engineering and computer science, managing privacy concerns and surveillance issues, overcoming resistance to change and mitigating potential job redundancies and losses due to automation. Furthermore, inadequate regulation, lack of standards, certifications, legal frameworks and weak data security measures pose significant issues. Developing appropriate regulations and acts is vital for successfully implementing the 4IR in Bangladesh.

Training and skill development

Many roles especially those involving repetitive tasks and physical labour are set to be displaced by disruptive technologies like IoT, robots and intelligent machinery. According to a recent

McKinsey report, approximately 5.7 million predominantly unskilled workers are projected to lose their jobs to automation in manufacturing industries over the coming decades. However, this technological shift is also expected to generate new job opportunities that demand cognitive abilities, technical skills, complex problem-solving, resource management and social skills. Government policymakers, academic institutions and training institutes must promptly invest in human capital and skills development. This investment should focus on upskilling, reskilling and providing long-term training to align with the demands of the 4IR and effectively bridge the gap between education and industry needs.

Infrastructural development

One of the most challenging aspects of integrating Industry 4.0 technologies is addressing security and risk concerns (65, 136, 137). The transition to online and interconnected systems significantly increases vulnerabilities to security breaches and data leaks. Such cyber risks are amplified due to the extensive data interconnectedness and potentially inadequate digital infrastructure (58, 68, 69). The issues are further complicated by the threat of internet hacking, where critical security problems are exacerbated by these interconnected systems and sometimes weak digital frameworks (60, 61, 65, 138). Additionally, in Bangladesh, the implementation of Industry 4.0 is hindered by infrastructural limitations such as underdeveloped road and transportation systems, high susceptibility to natural disasters and underdeveloped technological device markets and production capabilities. These factors create significant barriers for key planners and stakeholders contemplating the transition to Industry 4.0 (138). Furthermore, adopting Industry 4.0 technologies demands substantial investments and research in several critical areas. These include expanding internet broadband services, enhancements in IT and cyber security and developing relevant cyber laws. This technological shift also necessitates a parallel evolution in the educational sector to equip the new workforce with the requisite skills to thrive in a digitally transformed industry (66, 60-62, 70, 138, 139).

Conclusion

This research explores the challenges and prospects of Industry 4.0 in Bangladesh, highlighting its potential to enhance productivity, improve resource efficiency and increase global competitiveness. However, significant challenges remain, including heavy reliance on technology, the absence of a cohesive framework and cyber security management. The study also highlights the need for strategic planning, critical technology applications and government support. It concludes with recommendations for future policy directions. Besides it includes altering agriculture with competence in the overall production system, including post-harvest management. Use of advanced technological innovation in crop agriculture, fisheries, and animal rearing is in the process of the 4IR. The amalgamation of AI, sky technology, automation, robotics, etc., has the potential to make quantum leaps to overall food system. Crop monitoring for pest and diseases, soil fertility, land suitability, etc., along with feed nutrition in animal rearing, hydroponics, vertical farming and forecasting will be covered with digital agriculture generating data base for AI and IoT.

Acknowledgements

The authors would like to extend their sincere appreciation to the Department of Agronomy, Bangladesh Agricultural University, Mymensingh, Bangladesh.

Authors' contributions

UKS conducted the investigation, performed formal analysis, curated the data and contributed to the review and editing of the manuscript. MTA was responsible for drafting the original manuscript, developing the materials and methods section, conducting the investigation and formal analysis, curating data and contributing to the study's conceptualization. SAU assisted with writing, formatting and took part in reviewing and editing the manuscript. GS was involved in the conceptualization of the study and contributed to the manuscript review and editing. MRU oversaw the project through supervision and administration, acquired funding, contributed to conceptualization and participated in reviewing and editing the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical issues: None

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Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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