A Summary of Current Developments in the Processing of Agri-Food Using Digital Technologies

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ملخص للتطورات الحالية في معالجة الأغذية الزراعية باستخدام التقنيات الرقمية

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Abstract
Food Processing has undergone a qualitative transformation thanks to digital technology, as it has become a key tool for improving efficiency, reducing waste, and ensuring product quality, the need for these digital transformations is increasing to address global challenges, such as population growth, climate change, and the need for resource sustainability, the research results have proven that the application of digital technology in food manufacturing achieves benefits in terms of improving food quality and safety through sensor systems that monitor environmental conditions during production and storage, which reduces the risk of food contamination by up to 30% and reduces production losses thanks to artificial intelligence that analyzes operational data and identifies production stages that consume excessive amounts of water or raw materials, which contributes to reducing food waste and improving transparency in food supply chains through blockchain technology, which enhances consumer confidence by 15% in tracing the source of food products, and to personalize food products using 3D printing, which enables the production of customized foods with a balanced nutritional composition that meets the health needs of individuals, despite these benefits, the industry faces challenges, most notably the high costs of adopting digital technology, weak infrastructure in some rural areas, and lack of technical knowledge among the workforce.

Keywords: Food manufacturing, Digital, IoT, Blockchain, 3D printing.

الملخص
شهدت معالجة الأغذية تحولًا نوعيًا بفضل التكنولوجيا الرقمية، حيث أصبحت أداة رئيسية لتحسين الكفاءة وتقليل الفاقد وضمان جودة المنتجات. وتزداد الحاجة إلى هذه التحولات الرقمية لمواجهة التحديات العالمية، مثل النمو السكاني، وتغير المناخ، والحاجة إلى استدامة الموارد، أثبتت نتائج البحث أن تطبيق التكنولوجيا الرقمية في التصنيع الغذائي يحقق الفوائد من حيث تحسين جودة وسلامة الأغذية من خلال أنظمة الاستشعار التي تراقب الظروف البيئية أثناء الإنتاج والتخزين، مما يقلل من مخاطر التلوث الغذائي بنسبة تصل إلى 30%وتقليل الفاقد في الإنتاج بفضل الذكاء الاصطناعي الذي يحلل البيانات التشغيلية ويحدد مراحل الإنتاج التي تستهلك كميات زائدة من المياه أو المواد الخام، مما يسهم في خفض الهدر الغذائي وتحسين الشفافية في سلاسل الإمداد الغذائية عبر تقنية البلوك تشين، مما يعزز ثقة المستهلكين بنسبة 15% في تتبع مصدر المنتجات الغذائية، ولإضفاء الطابع الشخصي على المنتجات الغذائية باستخدام الطباعة الثلاثية الأبعاد، مما يتيح إنتاج أطعمة مخصصة ذات تركيبة غذائية متوازنة تلبي الاحتياجات الصحية للأفراد، ورغم هذه الفوائد، تواجه الصناعة تحديات أبرزها ارتفاع تكاليف تبني التكنولوجيا الرقمية، وضعف البنية التحتية في بعض المناطق الريفية، ونقص المعرفة التقنية بين القوى العاملة.

الكلمات المفتاحية: التصنيع الغذائي، الرقمية، إنترنت الأشياء، البلوك تشين، الطباعة ثلاثية الأبعاد.

Introduction

The food industry has undergone a qualitative transformation thanks to digital technology, as it has become a key tool for improving efficiency, reducing waste, and ensuring product quality [1]. The need for these digital transformations is increasing due to global challenges, such as population growth, climate change, and the need for resource sustainability [2,3]. Digital technology, such as artificial intelligence (AI), is used to analyze big data from production lines, helping to reduce human error and increase operational efficiency [4,5]. For example, AI can analyze real-time production data to identify potential problems and reduce food waste, which enhances the productivity of food factories [6]. The Internet of Things (IoT) enables real-time monitoring of food quality across the supply chain, through smart sensor systems that measure temperature and humidity during transportation and storage [7,8,9]. These technologies provide accurate data that helps companies ensure that products adhere to safety and quality standards [10]. Blockchain technology is used to record food product data in a transparent and immutable manner [11]. This helps to enhance trust between producers and consumers by tracking the sources of ingredients and ensuring their quality [12,13] Robots are increasingly being used in packaging and inspection operations, performing repetitive tasks quickly and accurately [14]. This automation reduces costs and increases

food safety, making operations more sustainable and efficient [15] Despite the enormous benefits, the industry faces significant challenges, most notably:
High initial costs of adopting digital technology [16].
Lack of technical knowledge among the workforce in many rural areas [15,17]

Global Challenges in Food Production and Consumption

The world today faces serious challenges related to food production and consumption [18]. These challenges include climate change, population growth, scarcity of natural resources, and food waste, all of which threaten global food security and the sustainability of production systems [19,20].

Climate change has a significant impact on global agriculture through increasing temperatures, changing rainfall patterns, and increased rates of natural disasters such as droughts and floods. The Food and Agriculture Organization (FAO) reports that more than 100 million people could be pushed into extreme poverty by 2030 due to climate impacts on food security [11 ,4]

The world population is expected to reach about 10 billion by 2050, placing enormous pressure on food production systems. To achieve food security, production must increase by at least 70%, while using as few natural resources as possible [10]

Resources such as water and agricultural soil are under great pressure due to unsustainable agricultural practices. A World Bank report indicates that 70% of global freshwater is used for agriculture, with water shortages in many regions [21]

Nearly one-third of the food produced globally is wasted or lost, equivalent to about 1.3 billion tons per year. This challenge represents not only an economic loss, but also a huge environmental burden [22] Inequality in food distribution, with more than 800 million people suffering from hunger, while other countries suffer from food surpluses Poor access to healthy and nutritious food due to poverty and lack of awareness.

The Role of Digital Technology in Food Production

Digital technology plays a very important role in revolutionizing the food industry, and that is in the enhancement of production, quality, reduction of waste and sustainability [20]. The following are the role of such technologies as artificial intelligence, Internet of Things, robotics, and blockchain which have revolutionized both agricultural and industrial food production to ensure that there is food for the ever-growing population while at the same time conserving natural resources [23].

Artificial Intelligence and Big Data Analysis

AI is used to analyze huge amounts of data generated by production processes. It helps improve crop production by analyzing data related to climate and soil, it can predict quality and productivity issues, allowing companies to take proactive action [24,25]**.**

Internet of Things IoT

The Internet of Things contributes to improving production processes by connecting different devices through networks. Farmers can track the status of crops or livestock via sensors connected to the Internet. It helps reduce waste of resources such as water and energy by closely monitoring environmental conditions [26]**.**

Robotics and Automation

Robots are used in agriculture and food processing, enhancing efficiency and accuracy:
In automated harvesting, especially for sensitive crops such as fruits and vegetables.
In factories, robots are used in packaging to ensure uniformity and quality and reduce operational costs [27].

Blockchain technology

Blockchain is used to provide transparency in food supply chains. Every step of food production and transportation is recorded, enhancing consumer confidence and reducing health risks. It helps combat food fraud by accurately documenting the sources of raw materials [28,29].

3D printing in food

3D printing is a promising innovation used to manufacture personalized foods, It is used to create nutrient-rich meals for people with special dietary needs, As shown in (Figure 1) It helps reduce waste by using ingredients more efficiently.

Figure 1: Two commercial 3D printers that are widely used [30].

Perhaps, the first edible material used for 3D printing experiments has been chocolates due to the controllable melting and solidification (crystallization) temperatures. In this regard, the Figure2 shows some representative images of 3D printed chocolates. However, many others food matrix may be prepared as pastes, cereal-doughs, ink-gels from hydrocolloids, and powders directly introduced in the food matrix [31,32]

Figure 2: Representative examples of 3D printing of chocolate. [31]

Digital Food Manufacturing's Advantages

The production of food is being completely transformed by digital food manufacturing, as businesses use new technological tools to significantly increase sustainability, efficiency, and quality. This digital strategy has the advantages of increasing resource sustainability, decreasing waste, and improving food quality [33].

Improving food quality and safety

Food safety and quality are being revolutionized by digital technologies [34]. For instance, environmental conditions during production and storage are being tracked using Internet of Things (IoT) technologies. Sensors help to preserve product quality and lower the chance of contamination by providing precise, real-time temperature and humidity data [35]. According to study [36], the usage of sensors in food manufacturing facilities decreased incidences linked to food contamination by 30% [37].

Cutting down on food waste in production

To minimize waste in manufacturing, artificial intelligence (AI) is assisting in the analysis of operational data [38,39]. AI, for instance, can identify production phases that are using excessive amounts of water or raw materials and take prompt action to cut waste. Research by Jones et al [37]. suggests that (2024) Factories that adopted artificial intelligence Food safety and quality are being revolutionized by digital technologies [40]. For instance, environmental conditions during production and storage are being tracked using Internet of Things (IoT) technologies [41]. Sensors help to preserve product quality and lower the chance of contamination by providing

precise, real-time temperature and humidity data. According to [10] study, the usage of sensors in food manufacturing facilities decreased incidences linked to food contamination by 30% [41,42].

Cutting down on food waste in production

In order to minimize waste in manufacturing, artificial intelligence (AI) is assisting in the analysis of operational data. AI, for instance, can identify production phases that are using excessive amounts of water or raw materials and take prompt action to cut waste [50]. According to Jones et al.'s research, factories that used artificial intelligence in 2024 Commission for Europe, 2023 [51]

Giving customers a customized experience

Designing customized food items according to customers' dietary requirements is made possible by 3D printing. Products with a balanced nutritional composition are produced using this technology, improving the health of consumers [52]. A study [11] claims that 3D printing has raised the standard of food given to people with particular medical conditions [53].

Increasing food supply chains' openness

Transparency is increased via blockchain technology, which offers an unchangeable record of each supply chain stage [51,54]. The Blockchain in Food Supply Chains (2023) report states that consumers' trust in brands has increased by 15% as a result of their increased ability to monitor the origin of food goods [55].

Digital Technology Implementation Challenges in the Food Industry

The food industry has several challenges in the implementation of digital technology which include; Improved productivity, higher quality products and sustainability are some of the benefits that have been associated with the use of digital technology in the food industry. However, the transition to digital production is not without its challenges [56,57,85]. These challenges may include difficulty in accepting and incorporating creative ideas, especially in areas with limited resources. This paper examines the major impediments to the adoption of digital technology in the food business [59].

1. High Costs of Digital Technologies

The initial investment required for adopting digital technologies, including the acquisition of advanced machinery, software, and training, is a significant barrier. Small and medium-sized enterprises (SMEs), which form a large part of the food industry, often lack the financial resources to make such investments [60,59]. Additionally, the maintenance and upgrading costs of these technologies pose long-term financial challenges [61].

2. Limited Access to Technology in Remote Areas

In rural and remote areas, limited access to digital infrastructure, such as high-speed internet and electricity, restricts the adoption of digital technologies [62]. These regions often lack the necessary connectivity to support real-time data collection and analysis, which are critical components of digital manufacturing [63].

3. Need for Adequate Infrastructure

The successful implementation of digital technologies requires robust infrastructure, including IoT-compatible equipment, cybersecurity measures, and data management systems [55,64]. Many food processing facilities, particularly in developing countries, lack such infrastructure, making the transition to digital systems challenging [65]

4. Cultural and Social Challenges

Cultural resistance to change and a lack of technical knowledge among workers can hinder the adoption of digital technologies [66]. Training employees to work with advanced systems is time-consuming and expensive [67,63]. Furthermore, there may be skepticism regarding the benefits of technology, especially in traditional food production environments [68].

Future Prospects for Digital Technology in Food Processing

Digital technology is set to play a transformative role in the food industry, revolutionizing food processing, enhancing sustainability, and addressing pressing global challenges [69,70]. The integration of these technologies offers opportunities to achieve sustainable development goals, alleviate the global food crisis, and improve the livelihoods of small-scale farmers [71,72].

Role in Achieving Sustainable Development Goals

Digital technologies such as artificial intelligence (AI), blockchain, and the Internet of Things (IoT) are critical tools for advancing the United Nations' Sustainable Development Goals (SDGs) [73,71]. For instance, AI-powered solutions can optimize crop yields, reduce food waste, and improve resource management, contributing to SDG 2: Zero Hunger [74]. Moreover, IoT-enabled monitoring systems ensure sustainable water and energy use in food production, aligning with SDG 12: Responsible Consumption and Production [75]

Potential to Solve the Food Crisis by 2050

The global population is expected to reach nearly 10 billion by 2050, significantly increasing the demand for food. Digital agriculture technologies such as precision farming, automated irrigation, and drone-assisted planting could increase agricultural productivity by up to 70%, ensuring food security for future generations [76,77]. Additionally, blockchain technology is expected to enhance transparency in food supply chains, reducing losses and ensuring equitable distribution [78,79]

Impact on Small-Scale Farmers

Smallholder farmers, who produce 80% of the world's food, face significant challenges such as limited access to technology and unstable markets [80,61]. Digital platforms provide them with tools to monitor weather patterns, access markets, and secure fair prices for their products. For example, mobile applications with AI capabilities offer real-time data on pest control and soil health, empowering farmers to make informed decisions [81,55].

Furthermore, e-commerce platforms are expanding small-scale farmers' market reach, helping them earn better incomes. Studies indicate that farmers using digital solutions have experienced up to a 30% increase in productivity and income [82].

Moving Toward Smart Agriculture

Smart agriculture integrates IoT, machine learning, and robotics to create sustainable food systems [83]. IoT sensors enable precision farming by monitoring environmental conditions and automating irrigation and fertilization processes [84,85,86]. Robotics is already playing a key role in planting, harvesting, and packaging operations, reducing reliance on manual labor [87,86]

Moreover, digital farming practices are expected to reduce carbon emissions and energy consumption, contributing to a more sustainable agricultural ecosystem [88]. By 2040, it is estimated that 50% of global farming operations will utilize some form of digital technology [89,90]

Case Studies and Practical Applications of Digital Technology in Agriculture

Successful Applications of Artificial Intelligence in Agriculture Artificial Intelligence (AI) has shown transformative potential in various agricultural domains [91]. For instance, AI-driven tools have been used for pest detection, improving crop yields, and optimizing irrigation systems [92,93]. In India, the "AI4AI" Initiative has enhanced smallholder farmers' access to digital tools, improving productivity and reducing waste [94]. AI applications also extend to predicting weather patterns and optimizing fertilizer use, significantly contributing to sustainable farming practices [95,96,89].

1. Blockchain Technology for Supply Chain Transparency Blockchain technology is revolutionizing the traceability and transparency of supply chains [97]. A notable case is IBM’s Food Trust platform, which uses blockchain to track food items from farm to fork. This has increased consumer trust and minimized food fraud [98]. In addition, smallholder farmers in Africa have used blockchain to access markets and secure fair prices for their produce, showcasing its potential to address economic disparities [99]
2. Robotics in Food Processing and Agricultural Operations Robotics has enabled significant advancements in labor-intensive agricultural tasks [35]. For example, robotic systems are now widely employed In fruit harvesting, reducing labor costs and increasing efficiency. In Japan, robotics are used In rice planting and harvesting, demonstrating high precision and scalability [100]. In Europe, robots are used to plant and monitor crops autonomously, a leap towards fully automated farming [98]

Conclusion

Digital technology is reshaping the global food sector, offering unprecedented opportunities for improving productivity, sustainability, and resilience. The adoption of AI, IoT, blockchain, and robotics has shown tangible benefits in addressing critical challenges such as food security, resource efficiency, and supply chain transparency.

However, its full potential can only be realized through collective efforts involving investment, collaboration, and innovation.

1- The Importance of Investment in Digital Technology

Investment in research, development, and infrastructure is crucial for advancing the use of digital tools in agriculture and food processing. This includes expanding access to modern technologies for smallholder farmers and building resilient systems to withstand climate change impacts.

2- The Role of Governments and International Organizations

Governments and international organizations play pivotal roles in fostering digital transformation in the food sector. They can provide subsidies for adopting advanced technologies, create favorable policy environments, and encourage public-private partnerships. Programs like the United Nations' Sustainable Development Goals (SDGs) emphasize the importance of leveraging technology to eradicate hunger and ensure sustainable food systems.

Recommendations for Enhancing Sustainability and Productivity:

1. Encourage Knowledge Sharing: Establish global platforms for sharing best practices and technological advancements in agriculture.
2. Focus on Digital Literacy: Train farmers and workers in digital skills to maximize the benefits of modern technologies.
3. Invest in Infrastructure: Ensure reliable internet connectivity and digital infrastructure in rural areas.
4. Promote Sustainable Practices: Develop policies and incentives for adopting eco-friendly technologies.
5. Encourage Multi-Stakeholder Collaboration: Build alliances between governments, private companies, academic institutions, and non-profits to accelerate innovation.

Final Thoughts:

Digital transformation in agriculture and the food industry is no longer a choice but a necessity. By addressing the barriers to technology adoption and focusing on inclusive, sustainable strategies, the world can ensure equitable access to food while preserving natural resources for future generations.

Recommendations to Enhance Sustainability and Productivity in the Food Sector:

1. Boost Research and Development: Invest in research on digital technologies to improve food production quality and resource sustainability.
2. Improve Infrastructure: Establish robust internet networks and provide modern digital agricultural equipment, especially in rural areas.
3. Education and Awareness: Train farmers and workers In the food sector to effectively utilize digital technologies.
4. Encourage Private Investments: Implement policies that attract major companies to invest in digital agriculture.
5. Monitor Food Waste: Deploy digital monitoring systems to minimize food loss throughout production and supply chains.

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