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Review

Smart Kitchens of the Future: Technology's Role in Food Safety, Hygiene, and Culinary Innovation

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Abstract

In recent years, there have been significant advances in the application of technology in professional kitchens. This evolution of "smart kitchens" has transformed the food processing sector, ensuring higher standards of food safety through continual microbial monitoring, quality control, and hygiene improvements. This review critically discusses the recent developments in technology in commercial kitchens, focusing on their impact on microbial safety, operational efficiency, and sustainability. The literature was sourced from peer-reviewed journals, industry publications, and regulatory documents published between 2000 and 2025, selected for their relevance to the assurance of food safety using emerging technologies especially for use in commercial kitchens. Some of the most significant of these technologies currently being employed in smart kitchens include the following: smart sensors and IoT devices, artificial intelligence and machine learning systems, blockchain-based traceability technology, robotics and automation, and wearable monitoring devices. The review evaluated these technologies against criteria such as adherence to existing food safety regulations, ease of integration, cost factors, staff training requirements, and consumer perception. It is shown that these innovations will significantly enhance hygiene control, reduce the levels of waste, and increase business revenue. However, they are constrained by high installation costs, integration complexity, lack of standardized assessment measures, and the need for harmonizing automation with human oversight. Thus, for the widespread and effective uptake of these technologies, there is a need for better collaboration between policymakers, food experts, and technology innovators in creating scalable, affordable, and regulation-compliant solutions. Overall, this review provides a consolidated evidence base and practical insights for stakeholders seeking to implement advanced microbial safety technologies in professional kitchens, highlighting both current capabilities and future research opportunities.

Keywords: food AI; smart kitchen; food blockchain technology; food organoleptic quality; food safety

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1. Introduction

1.1. Overview of Microbial Safety Challenges in Professional Kitchens

Professional kitchens, often referred to as commercial or institutional kitchens, are high-demand food preparation spaces that cater to restaurants, hotels, catering services, and other food establishments. Although professional kitchens are integral to the global food service sector, they encounter numerous challenges in ensuring microbial safety majorly because these environments are characterized by high operational intensity, frequent raw ingredient handling, and complex workflows, which raise the possibility of microbial contamination [1]. Microbial contamination leading to the spread of foodborne pathogens, including *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes*, is a continued concern due to its impact on human health and the economy. The combined annual impact of nontyphoidal *Salmonella*, *E. coli* O157, *L. monocytogenes*, and *Campylobacter* on human health in the United States is estimated to be between USD 9 and USD 11 billion, with over 2 million foodborne illnesses, 31,000 hospitalizations, and 700 fatalities [2,3]. Poor hygiene practices, cross-contamination, and inadequate temperature control are some of the most common causes of microbial risks in both domestic and professional kitchens [4]. These challenges are further heightened by the increasing sophistication of culinary processes and the escalating consumer demand for minimally processed, fresh, and exotic food that often bypass traditional safety barriers [5].

Furthermore, the increasing prevalence of antimicrobial-resistant (AMR) microorganisms including pathogens, commensal species, environmental microbes, and spoilage organisms poses a significant challenge for microbial safety in professional kitchens. Strategies to eliminate microorganisms in kitchens, including smart innovations, do not necessarily distinguish between pathogenic and non-pathogenic agents and thus should be sturdy enough to effectively eliminate both AMR and organisms, pathogens, and commensals. While AMR pathogens are a direct public health concern due to their ability to cause foodborne illness, non-pathogenic AMR organisms can also act as reservoirs of resistance genes, facilitating horizontal transfer to pathogenic strains [5]. These microorganisms may survive traditional cleaning and sanitization practices, persist on kitchen surfaces, and contribute to both contamination risks and a reduced shelf life of food products. Furthermore, antimicrobial resistance in many foodborne microorganisms originates from the farm through the excessive use of antibiotics within agriculture and animal husbandry, leading to its presence in raw ingredient kitchens [6]. If these organisms are not inactivated through the cooking process or decontamination of equipment and preparatory surfaces, there is a risk of them contaminating finished products and being consumed, leading to possible public health issues. Professional kitchens are more susceptible to AMR-related risks due to their reliance on high-volume food production processes that amplify opportunities for contamination and cross-contamination. For example, it has been shown that poor handling of raw meat can lead to the spread of these organisms to ready-to-eat foods through contaminated cutting boards, utensils, or staff hands [5]. Limited understanding of AMR risks can lead to insufficient adherence to food safety protocols such as frequent hand washing, proper storage temperatures, and periodic high-touch surface cleaning and sanitizing, further aggravating the problem [6]. The consequences of these risks are far-reaching, impacting not only public health but also the reputation and operational efficiency of food establishments. Hence, education and training programs geared towards increasing the kitchen staff's awareness of the risks of AMR and effective safety practices are important for engendering a vigilant culture.

1.2. Importance of Monitoring Microbial Safety for Public Health and Culinary Excellence

Microbial safety plays an equally important role in safeguarding public health and ensuring that high standards in gastronomy and hygiene are upheld, particularly in professional kitchens where large quantities of food are prepared and served. Considering this, the Food and Agricultural Organization (FAO) of the United Nations has over the years set minimum requirements that foods from commercial sources must meet. These are outlined in a series of guidelines and standards including microbiological criteria for pathogens such as *Salmonella* spp. and *Listeria monocytogenes*, maximum limits for pesticide residues and heavy metals, and hygienic handling and storage standards to prevent contamination [7]. Similarly, several regional and country regulatory organizations have benchmarks for monitoring food safety compliance. According to the World Health Organization, many foodborne diseases may lead to long-lasting disability and deaths [8]. Poor hygiene in professional kitchens may lead to serious outbreaks, the destruction of consumer trust, and the reputation of food companies being put at risk. Sometimes, food contamination happens upstream outside the kitchen (contamination of agricultural raw material) such as the *E. coli* O104:H4 incident in Germany in 2011, which was attributed to contaminated fenugreek sprouts, resulting in 386 cases of illness and 54 deaths [9]. This emphasizes the necessity of rigorous monitoring systems at every stage of food production, from sourcing and preparation to final consumption and the importance of intermediate systems in kitchens to aid in the detection of such raw product contamination. From a public health point of view, microbial monitoring is necessary to reduce the risks associated with microbial contamination, as it enables compliance with Hazard Analysis and Critical Control Points (HACCP) [7]. HACCP provides a preventive, science-based framework for food safety that focuses on identifying potential hazards that could be biological (e.g., *Salmonella*, *Listeria*), chemical (e.g., cleaning residues), and physical (e.g., metal fragments); and determining the specific Critical Control Points (CCPs) in the food production chain where these hazards can be effectively controlled, prevented, or eliminated [10]. This systematic approach allows targeted interventions at key stages such as cooking, chilling, or packaging, thereby minimizing contamination risks.

It is important to note that microbial safety challenges vary significantly between developed and developing countries. While developed nations often benefit from advanced monitoring technologies, strict enforcement mechanisms, and robust infrastructure to control foodborne threats, many developing countries still face limitations in laboratory capacity, trained personnel, and regulatory oversight. These factors culminate in the delayed detection, response, and control of foodborne threats. Developed countries, on the other hand, have well-established systems that can detect, trace, and address contamination incidents more quickly due to integrated databases, consistent legislative frameworks, trained inspection teams, and routine surveillance programs that are often underdeveloped or inconsistently applied in low-resource settings [11]. In the Global West, food regulatory bodies and committees set up systems for the assurance of food safety and quality including ranking systems such as the food hygiene rating system in England, Wales, and Northern Ireland [12]. In Canada, Health Canada has the responsibility for setting up food safety standards while the Canadian Food Inspection Agency (CFIA) carries out the monitoring across the country and enforces standards set by Health Canada [13]. The CFIA's Food Safety Recognition Program serves the same purpose as the food hygiene rating system of other countries and works mainly by supporting industry-led food safety initiatives [14]. These systems are geared towards reducing the risks associated with the consumption of unwholesome foods and increasing consumer confidence in commercially produced foods. However, many developing countries like Nigeria do not have an equivalent of a national

food hygiene rating system that is standardized nor robust surveillance systems, which poses challenges in monitoring microbial safety [15].

Apart from the public health perspective, microbial safety is also a crucial part of culinary excellence. Indeed, excellence in gastronomy requires not only creativity and innovation but also an uncompromising attitude towards safety, hygiene, and quality. Culinary techniques such as sous vide cooking and fermentation, while offering unique flavors and textures, could also create environments that may be conducive to microbial growth if not managed properly [16,17]. For instance, sous vide cooking is based on low-temperature cooking for long times and, if not well followed, it allows the growth of anaerobic pathogens such as *Clostridium botulinum* [18]. Likewise, fermentation involves specific microbial associations, and any microbial imbalance impairs both safety and flavor [17]. Hence, integrating microbial monitoring into gastronomy is very important for ensuring that culinary excellence is not achieved at the expense of the consumers' well-being.

1.3. The Role of Technology in Enhancing Food Safety

In recent times when food production methods are becoming more complex, traditional safety measures must be augmented by technological innovations to keep pace with emerging challenges surrounding food safety [19]. Advanced tools and methods for early detection and risk assessment are essential in professional kitchens to build resilient food systems, enabling them to meet up with national and international food safety priorities by enhancing preparedness for the prevention of, mitigation of, and response to emerging microbial risks. Integrating smart sensors, Internet of Things (IoT) devices, and artificial intelligence (AI) into food production settings has enabled the real-time tracking of critical safety parameters, such as microbial load [20]. For instance, real-time monitoring tools, such as biosensors, offer real-time data on microbial contamination levels, thereby allowing for the early detection of contaminants [21]. Embedding these biosensors and physical/conventional sensors into smart kitchen equipment enables the continuous monitoring of microorganisms, their metabolites, toxins, allergens, and other critical parameters including the temperature and pH, warning users of deviations well before they become safety concerns.

Luo and Alocilja [22] developed a portable nuclear magnetic resonance-based biosensor for the rapid monitoring of *E. coli* O157:H7 in real sample matrices, which detects *E. coli* O157:H7 as low as 76 CFU/mL in water samples and as low as 92 CFU/mL in milk samples. IoT and machine learning-enabled hazardous gas detection systems, as described by Kumar et al. [23], provide the real-time detection of different hazardous gases such as CH_4, CO, liquid petroleum gas (LPG), volatile organic compounds (VOCs), and odor responses released from the kitchen, ensuring the preservation of gases, food safety precautions, and preventing accidents in the kitchen. Japanese companies like Kewpie and Fujitsu utilize AI technologies, such as Google's TensorFlow, for detecting defective food ingredients and AI models for monitoring kitchen staff to ensure compliance with strict kitchen hygiene standards, thereby enhancing food safety during processing and preparation [24]. Integrating these tools and techniques into professional kitchens not only promotes operational efficiency but also reduces human error, one of the most common causes of foodborne outbreaks. Real-time monitoring capabilities make food safety systems dynamic and responsive, allowing contamination risks to be detected at the earliest stages before they get out of control. For example, IoT-based refrigeration monitoring systems have been shown to substantially reduce abnormal temperature events and enable faster responses to problems. Commercially deployed IoT refrigeration remote monitoring solution systems incorporate automated alarm notifications that enable real-time updates to be sent when the temperature fluctuates outside of a set range, allowing foodservice operators

to act on temperature deviations immediately, reducing the risk of spoilage and near-miss contamination events [25].

2. The Evolution of Food Safety in Kitchens

Food safety has been transformed with time, from the growing understanding of microbial risks and the implementation of regulations to technological development. Over time, conventional methods of hygiene and preservation have been replaced by highly developed and technological solutions to suit modern professional kitchen needs. Traditionally, microbial safety and food hygiene in the kitchen have depended on various crude preservation methods such as salting, smoking, drying, and fermentation to prevent microbial growth [26]. Such practices originated out of necessity, long before microorganisms were ever identified. While these practices were effective to some extent, they lacked the precision to detect and control microbial hazards; thus, outbreaks of foodborne illnesses were a recurring challenge [27]. In all, food safety in the kitchen has evolved through an amalgamation of historical practices, regulatory frameworks, and technological innovations. These have transformed food safety from a reactive process into a proactive, scientifically driven discipline that enables professional kitchens to provide both public health protection and culinary excellence.

2.1. Historical Practices in Microbial Safety and Food Hygiene

In the early days of food preparation, microbial safety and hygiene were controlled by necessity and tradition-based methods rather than scientific understanding. Given that food and water are such essential physiological requirements for survival, humans must have developed some kind of adaptive strategy early in their evolutionary history to prevent foodborne illnesses as much as possible, most likely by a combination of instinctive behavior and trial and error [27]. For instance, mediaeval people washed their hands with water before eating, and they also avoided drinking contaminated water; the Egyptians had a food safety practice where male oxen were examined before eating. The animal was eaten following an initial ritual, and the animal was examined carefully to make sure that it was not sick [28]. From the ancient Chinese Confucian Analects from 500 B.C., there were clear warnings against the consumption of sour rice, rotten fish, meat, and other food products that appear stale or undercooked [29]. Archeological and paleontological records indicate that approximately 8000 to 10,000 years ago, humans began to experience problems related to food spoilage and illness caused by food consumption. These challenges included the spread of foodborne diseases resulting from unhygienic preparation practices and rapid spoilage caused by improper storage conditions [30]. They arose as early as when humans began to transition from hunting and gathering to more complex methods of food production requiring greater organization and technological adaptation. Moreover, it is likely that the growth of human populations, possibly in part due to the availability of stable food resources, further exacerbated these problems [27].

The difficulties inherent in producing, storing, and processing foods in early agricultural societies made microbial safety a serious concern. Food preservation techniques such as salting, drying, and fermentation were probably developed as primitive means to protect food from microbial hazards [26]. These techniques not only responded to immediate problems of spoilage and contamination but also laid the foundations for the more formal approaches to food safety and hygiene that exist today. While these techniques were effective to prevent spoilage, they were inconsistent and could not address all microbial risks. A general ignorance of pathogens such as *Salmonella*, *E. coli*, and *Listeria* meant that foodborne illnesses were common [27]. Not until the late 19th century did pasteurization, a process that kills many kinds of bacteria in foods, become a standard practice, greatly

reducing the incidence of some foodborne illnesses [31]. During this time, the first microbiologists, including Louis Pasteur, started to comprehend and manage the microbial causes of foodborne illness, food spoilage, and disease. The early 20th century saw the advent of refrigeration, which further decreased the risk of microbial contamination [32]. While these historical practices laid the groundwork for modern food safety, most of them failed to address the sophistication of microbial contamination that occurred in most professional kitchens. It was only through scientific discovery that the foundation was laid for the development of systematic and reliable food safety measures, leading to the improvement in the microbiological quality of our food supply today [32].

2.2. Key Regulations and Standards (e.g., HACCP, FSMA)

The introduction of food safety legislation and standards into the food processing environment and commercial kitchens provided the turning point towards the control of microbial food safety risk. One of the first principles to adopt a proactive rather than retrospective approach was the HACCP system developed in the 1960s by NASA and the Pillsbury Company [33]. HACCP identifies critical control points in the manufacture of foodstuffs where hazards, whether biological, chemical, or physical, are most likely to occur and adopts control measures to reduce risks. With assistance from the Food and Drug Administration (FDA), the use of HACCP management systems expanded throughout the food processing industry in the 1970s and has become an international benchmark, allowing for a systematic approach for ensuring food safety [34]. Establishing public health-oriented goals or standards that all food enterprises must adhere to was the main objective of the HACCP rule-making process, which aimed to promote improvements in food safety practices. One important aspect of this idea is that by setting goals or standards, innovation and modifications will be encouraged to lower the risk from biological, chemical, and physical sources of foodborne hazards while also giving organizations a means of holding them responsible for reaching acceptable standards of food safety performance [34].

In Europe, major food safety incidents such as the 1999 dioxin contamination of poultry feed in Belgium and the Bovine Spongiform Encephalopathy (BSE) crisis that occurred in the UK reflected weaknesses in food safety governance. These scandals underlined the need for urgency in reform and hence the formation of the European General Food Law in 2002. By keeping scientific risk assessment and risk management distinct, this marked a significant turning point in the European Union's administration of food safety and ensured that decisions were made impartially [33]. The European Food Safety Authority (EFSA), an independent organization tasked with risk assessments, scientific advice, and risk communication about hazards related to the food chain, was established as the cornerstone of this reform [35]. This structure was designed to follow the model of the National Academy of Sciences Redbook, prioritizing scientific integrity and transparency in risk assessments. Meanwhile, the European Commission would assume the role of risk manager by making proposals on regulatory directives adopted by the European Parliament and member states. Its directives are then adopted as national legislation by different countries, ensuring uniform food safety within the European Union [33].

By the early 2000s, there was a global agreement on the fundamental components of a contemporary, successful strategy for controlling food safety. The Codex Alimentarius (Latin for "Food Code") Commission released "Guidelines for Strengthening National Food Control Systems" [36]. In the report, the consensus between the Food and Agriculture Organization of the United Nations and World Health Organization outlined food safety systems that facilitate risk-based management from farm to table—that is, systems that are preventative rather than reactive and are put into place by science-based regulations that permit ongoing improvement. Informed by strong public health monitoring systems, the

paper encouraged the adoption of common risk management instruments like traceability and recall systems, HACCP and preventive control systems, good manufacturing and agricultural practices, and others. Discussions on how to create more dependable food safety governance at the national and international levels were sparked by these developments. Although each country's reforms varied somewhat, they were all influenced by the agreement reached at the multilateral talks at CODEX.

The Food Safety and Modernization Act (FSMA), enacted in the United States in 2011, expanded the foundational concepts of HACCP with an integrated strategy for improved food safety [33]. The FSMA emphasized preventive controls, supply chain transparency, and traceability to minimize microbial risks. The act introduced stringent requirements on food establishments, including professional kitchens, to identify potential hazards and implement science-based control measures. The FSMA also strengthened the FDA's enforcement capabilities by giving them obligatory recall authority. Additionally, it called for the development of more robust traceability systems, more frequent food business inspections, more documentation for high-risk items, and improved federal–state collaborations. Furthermore, the FSMA ensured that importers were made responsible for confirming that their suppliers have sufficient preventive measures [37].

Many Latin American nations have progressively integrated HACCP principles into national regulations to meet Codex Alimentarius Commission guidelines and align with the requirements of the export market. For example, in Brazil, there is an established system of food safety control and regulation that occurs at the federal and regional levels. With Brazil being a member of the Codex Alimentarius Commission, agencies such as the Ministry of Agriculture, Livestock, and Food Supply (Ministério da Agricultura, Pecuária e Abastecimento, MAPA) and the Ministry of Health, through the National Health Surveillance Agency (Agência Nacional de Vigilância Sanitária, ANVISA), are responsible for implementing federal and regional regulations that comprise good manufacturing practices (GMPs), standard operating procedures (SOPs), and HACCP programs in order to meet Codex guidelines and WHO directives [38].

Countries in the Asia-Pacific region like China have also updated their food safety regulations considering the vast regional diversity of the country as well as lessons learned from global best practices. The centerpiece of these reforms is China's Food Safety Law, first introduced in 2009 and amended in 2015, which stipulates an overarching governance structure based on co-regulation—a hybrid of industry self-regulation and legislative oversight by government authorities [38]. This framework unifies the regulation and supervision of food and drug safety under principal government departments, adheres to a farm-to-fork approach, and includes robust food safety risk surveillance and evaluation mechanisms and operator responsibility obligations [39]. Co-regulation has been at the core of improving quality and safety standards by ensuring private sector practices are underpinned by legislative approval. There is also empirical support for this; a survey of 27 large and medium-sized Chinese food companies reported that many had introduced HACCP systems, not only to meet domestic safety requirements but also to improve their international competitiveness [40].

These regulations ensure compliance and accountability and further create a culture of safety in professional kitchens.

3. Technological Innovations in Microbial Monitoring

The integration of different advanced technologies in professional kitchens has transformed the way microbial safety is monitored. These innovations not only protect public health but also raise the standards of gastronomy, as chefs can now focus on creativity without compromising food safety. In the culinary industry, maintaining a good standard of

microbial safety is key to ensuring that food is safe and fit for consumption. The advent of modern gastronomy has made the kitchen sophisticated; for this reason, there is a growing demand for advanced microbial monitoring. Traditional microbiological techniques such as culturing are usually time-consuming and labor-intensive [41]. To address these lapses, modern microbial detection systems have been adopted. Technologies such as biosensors, polymerase chain reaction (PCR)-based assays, and next-generation sequencing (NGS) have transformed microbial safety procedures by providing real-time data and high sensitivity in detecting microbial pathogens [42–44]. Other technological innovations include real-time monitoring instruments for microbial contamination and point-of-care technologies (POCTs) for food safety analysis, ensuring that a food processor demonstrates compliance with specific safety standards [19,21]. For instance, the biosensors being developed for the real-time detection of pathogens such as *E. coli*, *Listeria,* and *Salmonella* mean that effective action against them can be considered on time in the kitchen environment [21].

Advances in POCTs have transformed food safety monitoring by enabling innovative and portable detection technologies, which can be incorporated into modern kitchens. Researchers have introduced microfluidic chip-based devices, such as those made from poly (methyl methacrylate) (PMMA) or polydimethylsiloxane (PDMS)-based chips, and paper-based devices including lateral flow test strips and three-dimensional paper-based microfluidic systems [19,45]. These emerging tools are finding increasing applications in the detection of contaminants in foods for their ease of access and efficiency. Wu et al. [46] presented a simple and sensitive aptamer-based biosensor for the rapid detection of *E. coli* O157:H7 in their study, which could detect as low as 10 colony-forming units (CFUs) of *E. coli* O157:H7. These technologies have been found to adhere to the ASSURED criteria—Affordable, Sensitive, Specific, User-friendly, Rapid and Robust, Equipment-free, and Deliverable to end users—qualifying them as highly promising and an alternative means to conventional benchtop detection that requires sophisticated equipment, trained personnel, and extended times for processing [19]. These devices detect food safety rapidly and easily, satisfying the emerging needs of kitchens to monitor microbial and chemical contaminants on-site in real time. Small, portable units that are also easy to operate enable kitchen workers to maintain appropriate safety standards against the rapid development cycles expected within food preparation today. As they continue to advance, these detection tools hold significant potential for shaping old protocols of food safety into more active, streamlined systems truly reflective of how kitchens function within today's technologies.

3.1. Smart Sensors and IoT Devices

In today's world, food safety is more important than ever, and rapid microbial detection tools play important roles in ensuring food safety in the kitchen. Tools such as advanced biosensors and microbial testing kits provide real-time results that allow food handlers to take immediate corrective actions. These provide real-time data that enhances food safety and quality. One key innovation in this area is the use of bio- and smart sensors to detect pathogens or their biomarkers. These technologies are designed to recognize these pathogens and their biomarkers, producing a signal that indicates the presence of contaminants. Smart sensor devices come in different configurations. Some of the devices measure parameters like temperature, humidity, and surface cleanliness, which are very important in preventing microbial contamination and they allow for the collection of environmental data automatically. For instance, temperature sensors ensure that food is stored at the optimum temperature; in the same vein, humidity sensors can detect moisture levels that could permit the growth of molds or bacteria in food [47]. Electrochemical biosensors can detect *Salmonella* or *E. coli* in minutes, allowing quicker intervention to keep food safe [44,48]. Adenosine triphosphate (ATP) testing is another essential tool in

microbial monitoring. Kitchen staff can check the cleanliness of surfaces like countertops, utensils, or cutting boards within seconds using a simple swab test. If the ATP levels are high, it indicates that sanitation is needed [49]. Although ATP does not tell the exact type of microbes present, it is still a very reliable way to tell that the kitchen is unclean. In the long run, the use of these sensors reduces the likelihood of foodborne illness.

Overall, smart sensors and IoT devices play an important role in professional kitchens to maintain food safety in real time. For instance, smart refrigeration systems alert kitchen staff about deviations from the set range so that corrective action may be taken to avoid spoilage and contamination by microorganisms. In determining the shelf life of chilled and frozen food products in a kitchen or cold chain, temperature control is a critical factor [50]. This is particularly important because maintaining a continuous cold chain with suitable temperature conditions at every stage of the supply chain is crucial in preventing food waste due to microbial spoilage [51]. Hence, technological innovations in this area have led to the development of a time–temperature indicator system using wireless sensors that monitor the temperature conditions in real time. The system will not only guarantee the best conditions for storage but also contribute to maintaining the critical control point criteria of international food safety standards, such as ISO 22000 and HACCP [52]. Shih and Wang [52] reported the implementation of this IoT-based methodology in one of the major food franchises in Taiwan. In this case, wireless sensors installed at different points in the storage and processing chain continuously collect temperature data. Later, such information was analyzed using the X–R control chart and then monitored and maintained for standards of food safety. The integration of the IoT into traditional methods of food safety can enable the kitchen operators to take decisive actions on frozen and cool storage for product integrity and safety along the value chain.

The incorporation of smart sensors and Internet of Things (IoT) devices into the kitchen industry has completely taken microbial monitoring to the next level. Internet of Things (IoT) devices enhance the capacity of these sensors by connecting them to centralized systems, which allows for remote monitoring and controlling. IoT devices send alerts to kitchen staff when food safety parameters deviate; this prompts immediate corrective action. This is important, especially in large-scale kitchens in which manual monitoring in such environments may be challenging and overwhelming. Moreover, machine learning algorithms can be integrated into IoT-enabled devices to help predict potential contamination based on environmental predictions by the sensors. This approach allows kitchens to address issues before they escalate [53]. Furthermore, because IoT-enabled solutions provide centralized dashboards that allow kitchen managers to monitor different kitchen environments from a distance, and even remotely control appliances such as ovens and refrigerators with their mobile phone, there is a greater control of the food chain system. This, in turn, allows timely intervention in case of any indication of microbial hazards. In their study, Hassan et al. [54] presented a smart kitchen project that demonstrates the potential of automation and real-time monitoring to enhance culinary operations. In this system, sensors continuously monitor temperature and humidity levels in the kitchen environment, ensuring optimal conditions for food storage and preparation. Built-in gas detection sensors in this system identify any gas leaks in the kitchen and alert the user if the gas pressure there rises above a predetermined point. Interestingly, this technology allowed the user to remotely control appliances like air conditioners, stoves, and freezers with their mobile phone. Utilizing this IoT technology in professional kitchens will enhance automated alerts and data logging, maintaining consistency in following food safety standards, thereby minimizing human error.

Application of IoT in Ensuring Food Safety

IoT-enabled food safety advancement entails utilizing real-time monitoring and control technologies to improve the operations of food quality and safety. When the IoT is paired with artificial intelligence (AI) tools like machine learning and deep learning, it can create precise models for recognizing, forecasting, and resolving complicated food safety problems [55]. Through the real-time monitoring of variables like temperature, humidity, and viscosity, manufacturers may optimize regulatory processes and product quality by leveraging the IoT in food processes like fermentation [56]. Additionally, IoT technology makes it possible to track product quality, environmental conditions, and traceability in food supply chains, which improves food safety protocols [57].

As shown in the context of China, utilizing the IoT in food safety management is a critical step towards enhancing the current food safety oversight systems [58]. IoT solutions such as sensor networks, radio-frequency identification (RFID) tags, cloud-based monitoring platforms, and real-time data analytics are being deployed across the food supply chain to track environmental conditions, detect contamination risks, and monitor compliance with GMP, SOP, and HACCP requirements [59]. However, there are still significant gaps towards achieving the item-level monitoring and tracing of prepackaged food, for instance, along its entire supply chain, from production and packaging to distribution, consumption, and final disposal. Current reliance on batch codes is imperfect, as they are easily counterfeited, and tracking at the item level with RFID, while efficient, is too expensive at scale. To address these limitations, researchers have proposed an IoT-enabled tracking and tracing system integrating RFID and QR code technologies to decrease the implementation cost. This approach comprises an evaluation of the causal factors of food safety incidents and early-warning modules for identifying them, including a data analytics service for translating real-time data into decision-making information, thereby facilitating timely decision-making and improving the overall safety management of the prepackaged food supply chain [60].

Furthermore, the study by Liu et al. [61] illustrated how IoT technologies were utilized in a pilot project in China to enhance food safety by making the processes of tracking and monitoring food supplies more efficient. Advanced technologies such as service-oriented architecture, global identification, and electronic pedigree systems provided real-time visibility into food supply chains, especially for fresh vegetables. The project offered the end users, customers, and food supervisors an easy interface from where informed decisions pertaining to food safety can be made by fusing data from the different stages of the supply chain. The system has been successfully deployed by Lushang Ltd. (Lushan, China), the largest food supplier in Shandong Province, with the evaluation results confirming its efficiency and effectiveness in ensuring safer food supplies, exemplifying how the IoT can bolster traceability and transparency, ultimately contributing to better food safety management [61].

3.2. Rapid Microbial Detection Tools

Early detection of pathogens is important in the reduction in health risks and timely corrective measures, especially in high-stakes settings like professional kitchens. Most of the traditional methods of microbial testing such as cell culture, PCR, and immunoassays take several days to give results and may require skilled personnel [62], which is highly unfeasible in fast-paced environments such as professional kitchens.

3.2.1. Advanced Biosensors and Microbial Testing Kits for Rapid Results

Rapid detection tools including advanced biosensors and microbial testing kits that give results within minutes have emerged, offering faster and more reliable results to

improve microbial monitoring practices and prompt corrective actions [63]. Biosensors, for instance, are increasingly being adopted for microbial detection in professional kitchens due to their high sensitivity, specificity, and ability to provide real-time data [64]. These sensors operate by converting biological interaction, such as the presence of microbial cells or biomolecules, into an electric, optical, or chemical output. Electrochemical biosensors, for example, detect bacterial pathogens, including *E. coli* and *Salmonella*, common contaminants in kitchen environments [21]. Studies have demonstrated that biosensor-based methods significantly reduce the time required for microbial detection while retaining accuracy comparable to traditional culturing methods. Cimafonte et al. [65] developed a novel microbial detection sensor by immobilizing anti-*E. coli* antibodies using the photochemical immobilization technique, which drastically reduces the workload of surface modification. The technique works through the selective photoreduction of disulfides in antibodies into thiols that interact with gold surfaces without interfering with the antigen recognition site. Using UV activation, antibodies were successfully immobilized on inexpensive gold electrode surfaces. The sensor was capable of detecting *E. coli* in water through electrochemical impedance spectroscopy, with the limit of detection at 3.0×10^1 CFU/mL within only 3.5 h of detection time. This therefore points to the fact that further advances in the methods of surface modification may result in highly sensitive microbial detection devices with relatively shorter running times and hence offer promising applications in food safety monitoring for professional kitchens.

Another emerging technology for rapid microbial detection is paper-based microbial testing kits. POCT advancements have focused on the development of microfluidic devices, especially microfluidic paper-based analytical devices (μPADs), which are becoming popular owing to their cost-effectiveness, ease of fabrication, and disposable nature in an environmentally friendly manner [66]. Their operation is based on capillary action that eliminates the use of sophisticated laboratory equipment, hence making them suitable for rapid testing applications. Studies have demonstrated that μPADs can efficiently detect microbial contaminants within minutes, making them valuable tools for food safety monitoring. Using paper-based analytical devices (PADs), Boehle et al. [67] created a low-cost assay to detect β-lactamase-mediated resistance. To determine its viability, the PAD was used to identify resistance in specific bacterial species isolated from environmental water sources and to detect β-lactam resistance in wastewater and sewage.

Similarly, Bisha et al. [68] developed a protocol that makes it possible for the rapid colorimetric detection of foodborne pathogens, including *E. coli*, *Salmonella* spp., and *Listeria monocytogenes*, from large volumes of agricultural water up to 10 L. Sterile Modified Moore Swabs (MMS) gauze filters in plastic cartridges were used to concentrate bacterial cells from water samples. Following filtration, swabs underwent either selective or non-selective enrichment for target bacteria. Detection was performed on microfluidic paper-based analytical devices impregnated with bacterial-indicative substrates that can react with specific bacterial enzymes, yielding distinct colored products that can visually identify bacterial detection. For added precision, digital images of the μPADs can be taken and processed with ImageJ software to yield more objective standardized results. This platform has multiple advantages, keeping in mind the fact that sometimes, through background microbiota or substrate degradation, false positives may occur. Considering that it is low-cost, user-friendly, sensitive (0.1 CFU/mL), and the results take about 24 h, it can be utilized in microbial safety monitoring for screening the water microbiological quality in agricultural and kitchen contexts.

3.2.2. Use of Adenosine Triphosphate (ATP) Testing for Surface Cleanliness

The necessity of monitoring the cleanliness of food contact surfaces and the success of cleaning and sanitation procedures is well acknowledged in the food industry [69]. Cleaning by itself can reduce the quantity of biological, chemical, and soil contaminants as well as the number of microbial cells, although it may not totally eradicate them [70]. Because of their speed, simplicity, cost-effectiveness, and quantitative results, ATP hygiene monitoring tests are becoming increasingly popular as the significance of evaluating the efficacy of on-site cleaning increases [71]. These tests measure surface-bound ATP, a marker for biological residues, offering real-time feedback on cleanliness levels. When ATP levels fall below a defined threshold, surfaces are deemed clean, indicating the effective removal of biological contaminants such as microorganisms and organic matter [70]. Hence, the versatility of ATP tests makes them valuable for verifying and validating sanitation standard operating procedures (SSOPs) and monitoring cleanliness within HACCP systems. They are also integral to hazard analysis and risk-based preventive control programs outlined under the U.S. FDA FSMA [70].

ATP tests are currently important in proving cleaning methods and the establishment of optimal sanitary procedures in the food processing operation. They are very important in the assessment of clean-in-place systems, where cleaning is performed without disassembling equipment and pipelines. Parameters such as the temperature, time, flow rate, and detergent concentration can be optimized by adding test contaminants and then checking for cleanliness using ATP tests [70]. A study conducted in the Shizuoka Cancer Centre Dietary Department Kitchen by Aoyama and Kudo [72] evaluated the effectiveness of disinfection methods using ATP swab testing to assess surface cleanliness in large-scale cooking facilities. The Japanese Ministry of Health mandates the use of sodium hypochlorite aqueous solution (HYP) to prevent secondary contamination on food preparation surfaces. The study compared two disinfection methods: HYP swabbing alone and a combination of surfactants followed by HYP swabbing. The results from the study showed that ATP testing was effective in validating surface cleanliness and optimizing disinfection protocols in food preparation settings. Similarly, in the study by Irie et al. [73], the cleanliness of milking equipment following manual and automated cleaning was compared using an ATP test.

3.3. Artificial Intelligence (AI) and Machine Learning (ML)

Food safety and microbiological testing are being transformed by AI and ML, which offer innovative tools for automated data analysis, predictive analytics, and process optimization. Traditional methods of food safety monitoring are being transformed by the unparalleled capabilities of these technologies to analyze enormous volumes of data, spot trends, and generate precise forecasts [74]. Overall, artificial intelligence (AI) and machine learning have become powerful tools in the culinary world by helping to make kitchens safer and more efficient. These technologies help monitor potential microbial risks before they become serious issues [75].

3.3.1. Predictive Analytics for Identifying Microbial Risks

One major advancement AI and machine learning brought was the use of predictive analytics to assess microbial risk. They use historical data (temperature, humidity, and other environmental factors) to identify patterns that could be indices of increased likelihood of microbial growth. For example, machine learning models can help predict surface contamination in the kitchen [53]. This allows managers to adjust their cleaning schedule or be on alert to maintain a safer food preparation environment.

The foundation of predictive analytics in microbiology is the idea that, with the use of mathematical and computational concepts, the behavior of microbes, no matter how com-

plicated, can be accurately recreated and replicated in nonbiological models [76]. Predictive microbiology offers insights into microbial ecology, contamination sources, and possible contamination sites by employing mathematical models to identify microorganisms of interest [77]. Such systems analyze data that emanates from environmental conditions, supply chains, and microbial profiles using both historical and real-time information to forecast contamination events [74]. This can help food producers and regulatory agencies to adopt preventive measures rather than reactive ones, reducing foodborne illness outbreaks and enhancing consumer safety. Through predictive analytics, we can predict and comprehend the behavior of microorganisms in food. Researchers and experts in food safety can create models that capture the dynamic interaction between microbes and their surroundings by utilizing statistical and mathematical methods [78]. These models provide a sophisticated simulation of growth patterns over time by accounting for a wide range of variables, such as microbial traits, nutrition availability, and environmental circumstances [74]. By doing this, predictive modeling helps us anticipate possible risks and take preventative action in addition to improving our comprehension of microbial behavior [79].

In addition to predicting microbial risks, these powerful tools help automate data analysis to monitor compliance. In large-scale kitchens, AI can automatically process data from IoT devices such as sensors and microbial detection tools to ensure that all values are within the acceptable range. If deviations occur, the system can instantly alert staff to take corrective actions [53]. AI is not just making the kitchen smarter but also enables staff to work smarter. AI systems can suggest best cleaning routines and predict where contamination is most likely to happen by analyzing how often different areas of the kitchen are used, thus saving time and effort [80]. For instance, temperature fluctuations in transit can be analyzed by a machine learning model to predict spoilage risks and give recommendations for storage conditions [81]. Cassin et al. [82] conducted a dose–response analysis using Monte Carlo simulation in conjunction with microbiological data to predict the risk of Hemolytic Uremic Syndrome (HUS) from *E. coli* O157:H7 in beef hamburgers. The model simulated pathogen behavior through processing, handling, and final consumption, assessing risk by different age categories. The authors compared the efficacy of various mitigation strategies, such as storage temperature control, preslaughter screening, and cooking temperature. The results indicated that the risk of illness was considerably reduced by using proper temperature monitoring to minimize bacterial growth at retail level. Limitations in this study included uncertainties in hygiene during processing and handling, which cannot be modeled for every step of production and consumption. They also explained that not all bacteria able to survive the cooking process would be infective and HUS risk cannot solely be attributed to bacterial dose.

Large databases of food safety data can be analyzed using machine learning algorithms to find trends and correlations that can guide decisions about food safety. This can assist in pinpointing risk areas and enhancing procedures for managing food safety [83]. Additionally, projections that may be used to detect potential issues with food safety before they arise can be produced using computer vision. Machine learning can assist in detecting possible food safety problems before they become an issue by tracking the status of food safety [74]. According to a study by Gougouli et al. [84], factors including storage temperature, microbial strain, and warehousing time significantly affect the microbial development in yogurt, which is indicated by symptoms such as mycelial production. As a result, the dairy business greatly benefits from predictive algorithms that can forecast fungal growth by examining these variables. By including these models into the final testing of yogurt products for fungal growth before market release, quality control procedures can be improved. Predictive models help identify the ideal circumstances for the

development of different microbial species in end-product challenge testing in these kinds of applications [77].

3.3.2. Automated Data Analysis for Compliance Monitoring

Another transformative application of AI and ML in food safety is automated data analysis. Most of the traditional methods for microbial testing require labor-intensive and time-consuming processes, mainly because trained personnel have to interpret the results. AI algorithms can quickly process big datasets from microbial testing kits, laboratory experiments, and sensor outputs, delivering actionable insights in real time [85]. This smoothens the way to compliance monitoring and ensures that food products meet regulatory standards before reaching consumers. In the study by Qin et al. [86], a novel multimodal optical sensing system was developed for automated and intelligent food safety inspection. The system is automated and counts, positions, and synchronizes the data of samples using real-time image processing and motion control, integrating some functions of artificial intelligence that could identify and label the target samples instantly. The performance of the system was verified by the fast identification of five foodborne bacteria: *Bacillus cereus*, *E. coli*, *L. monocytogenes*, *Staphylococcus aureus*, and *Salmonella* spp., with 98.6% classification accuracy using the linear support vector machine model. Considering the compact and portable nature of this system, it is appropriate for field and on-site food safety inspections in regulatory and industrial applications, offering an efficient and automated means for compliance monitoring.

Furthermore, AI and ML make it easier to detect anomalies and perform root cause analysis in production environments. These technologies monitor production lines continuously to identify any deviation from standard operating procedures, flag potential contamination risks, and suggest corrective actions—all bringing more precision to quality control and reducing product recalls [85]. The SCAMP-ML platform developed by Iuhasz et al. [87] represents an advanced system for automatic data analysis and compliance monitoring for Industry 4.0. At its core, it is data-agnostic and was designed for high interoperability, which makes it easy to integrate with various sensors and devices emanating from diverse industries. Core functionalities of the platform include cycle detection, which matches sensor data streams against user-defined templates; cycle identification, which clusters the detected cycles and identifies production events; and cycle anomaly detection, focused on identifying irregular cycles and root cause analyses for predictive maintenance. These contribute to data-driven decision-making and operational efficiency. The results from the study demonstrated that SCAMP-ML showed very strong predictive performances in three phases: the detection of the production cycle, analysis and identification of the cycle, and anomaly detection. The precision and scalability of the platform present the potential to improve compliance monitoring, production efficiency, and quality control automation in industrial contexts [87].

3.4. Blockchain Technology

Blockchain technology is an emerging, innovative tool in supply chain and food safety, with real-world applications in enhancing traceability and transparency, from farm to fork. It can be employed to securely record and share microbial testing data from food products and processes, thereby enhancing food safety and ensuring transparency across the supply chain. It is fast becoming a game-changer in the food industry, improving the traceability of products and ensuring that food stays safe from the farm to the kitchen and to the table. The use of blockchain technology allows everyone involved in the supply chain to track a product every step of the way; this creates transparency and accountability. This technology offers a significant advantage by providing a transparent and unalterable record

of a food product's origin and handling throughout the supply chain, which is crucial for not only ensuring food traceability, but for the assurance of microbial safety, as potential contamination can happen at any stage from harvest to storage. When a food safety issue occurs, blockchain technology enables swift identification of the source of contamination by providing detailed records of the product's journey [88,89].

Although traditionally used for secure financial transactions, blockchain's decentralized, tamper-proof ledger system provides unparalleled advantages for real-time microbial monitoring, data integrity, and compliance within smart kitchens [57]. Blockchain can be integrated with IoT sensors, hygiene monitoring systems, and automated inventory tools to record microbial test results, verify ingredient provenance, document compliance with cleaning and sanitation schedules, and track waste generation and disposal [90]. For example, temperature logs from refrigerators, results from ATP or rapid microbial testing, and data from waste-sorting devices can be securely stored on an immutable ledger, making them instantly accessible to kitchen managers, auditors, and regulators. This ensures complete transparency in the assurance that relevant information regarding probable microbial contamination goes to everyone in real time [90].

A recent study developed an IoT-based fire prevention system that was integrated with the Ethereum blockchain to create a verifiable record of fire risk events. The plug-in device connects to a stove's outlet and, upon detecting smoke, automatically cuts power and sends an alert through the Google Firebase webservice to the homeowner's smartphone. Homeowners can restore power using a nearby wireless button. The system operates seamlessly without requiring complicated electrical connections and installation. All trigger events are recorded on a blockchain smart contract, ensuring secure, tamper-proof logging, while companion Android and iOS apps allow remote monitoring and stove control [91]. This IoT–blockchain fire prevention system finds high relevance within smart kitchens, allowing not only the detection of hazards like smoke but also taking autonomous preventive action by cutting power, which reduces the risk of kitchen fires. Its integration with blockchain technology ensures tamper-proof event logs, which provide verifiable safety data for insurance claims, compliance, or kitchen safety audits.

Outside smart kitchens, blockchain technology could also enhance food traceability in every stage and help in the identification of contaminated products, risks, and frauds as early as possible. For instance, Walmart and Kroger were among the first businesses to adopt blockchain and integrate it into their supply chains, originally concentrating on case studies with Chinese pork and Mexican mangoes [92]. According to the preliminary findings of the research, it took 6.5 days to track a package of mangoes from the grocery store to the farm where they were grown using conventional methods, but blockchain technology made this information available in a matter of seconds [93]. Recently, Tian [94] proposed the integration of blockchain technology with the IoT to enable real-time physical data monitoring and tracing using the HACCP framework for the continuous monitoring of critical parameters that are essential to ensure food safety across production and distribution chains. This integration is particularly crucial for maintaining the cold chain during the transportation of perishable food items, where temperature fluctuations can compromise microbial safety [95]. Within a smart kitchen environment, the same approach can be applied to monitor storage temperatures in refrigerators and freezers, track cooking and hot-holding temperatures, and log sanitation or allergen-control procedures. All CCP data is stored on a blockchain, making it easily auditable and impossible to tamper with, ensuring compliance, accountability, and rapid response if a hazard is detected.

Despite these advantages, the adoption of blockchain in food safety faces several limitations, including the high costs of implementation, lack of interoperability between different blockchain systems, limited technical expertise among small and medium-sized

enterprises, and regulatory uncertainty in some regions [89]. In developing countries, additional drawbacks such as a lack of digital infrastructure and low internet adoption could deter mass deployment. Potential solutions include the development of open-source blockchain platforms that lower the barriers of entry, enabling customization at a minimal cost of licensing fees, and government-led pilot programs that demonstrate feasibility, provide subsidies, and create regulatory frameworks to support adoption [96]. Public–private partnerships can further help build capacity, standardize protocols, and ensure that blockchain benefits are accessible to stakeholders across the entire supply chain, not just large corporations.

3.5. Robotics and Automation

In recent years, technological advancements have revolutionized the food industry, by introducing automation and robotics, making the production process more efficient and safer. One of the most important areas of innovation involves the deployment of robots in food preparation and cleaning processes to reduce human contamination. This development will help solve some of the most important issues on hygiene, foodborne illnesses, and operational efficiency in food production environments. Since the introduction of robotics and automation in professional kitchens, there has been a recorded decrease in food contamination by humans. In a kitchen environment where hygiene is critical, robots offer a reliable and efficient solution to reduce contamination. They are programmed to perform repetitive tasks such as chopping and slicing without human contact. This significantly reduces the risk of cross-contamination that could occur when food is handled by multiple people [97]. Thus, by automating food prep procedures, robots can ensure more hygienic meals are produced. In addition to preparing food, robots also help to clean the kitchen environment. Automated systems equipped with sensors and cleaning agents can decontaminate surfaces via cleaning-in-place (CIP) protocols more thoroughly as compared to manual methods. Similarly, automating UV and visible light disinfectant devices can be utilized in sanitizing more difficult-to-reach areas of professional kitchens including preparatory surfaces and conveyor belts [98,99]. They can also work in conjunction with other smart technologies such as the sensor and AI systems to monitor the levels of cleanliness in real time and be used to sterilize countertops, utensils, and cooking equipment, eliminating harmful pathogens in a faster and more effective way. This data can be collected and aid in the decision-making process by alerting concerned kitchen staff to areas that require a higher standard of cleaning for the assurance of microbial safety [99]. However, automation using robots in the kitchen could reduce the kitchen workforce as it can make kitchen staff redundant.

Robots in Food Preparation and Cleaning to Minimize Human Contamination

Food handlers in food processing facilities are directly responsible for the vast majority of the 76 million cases of foodborne diseases that occur in the US each year [100]. Cross-contamination from another raw food product that a person has just handled or from infected individuals handling the food can introduce transient foodborne microorganisms. The presence of human hair, skin, nails, or other things in food can potentially lead to food contamination. Because transient organisms are easily spread by hand until they are eliminated by the mechanical friction of soap and water washing or eliminated using an antiseptic solution, they are especially dangerous [100]. Hence, food robots are being integrated into the preparation of food nowadays, such as slicing, dicing, mixing, and packaging. These automated systems are designed to handle these repetitive tasks that require precision without microbial contamination, usually associated with human contact [97]. An example is chef robots (shown in Figure 1), which are suitable even in

the preparation of native dishes such as okonomiyaki. In slaughterhouses, for instance, automation processes with robots are being introduced to overcome labor issues [101]. The Danish Meat Research Institute (DMRI) recently created bung droppers for the carcasses of sheep and pork. According to reports, the bung dropper, which can handle 900 carcasses per hour, successfully eliminates 50% contamination in the pork slaughtering process when compared to manual operator handling [102].

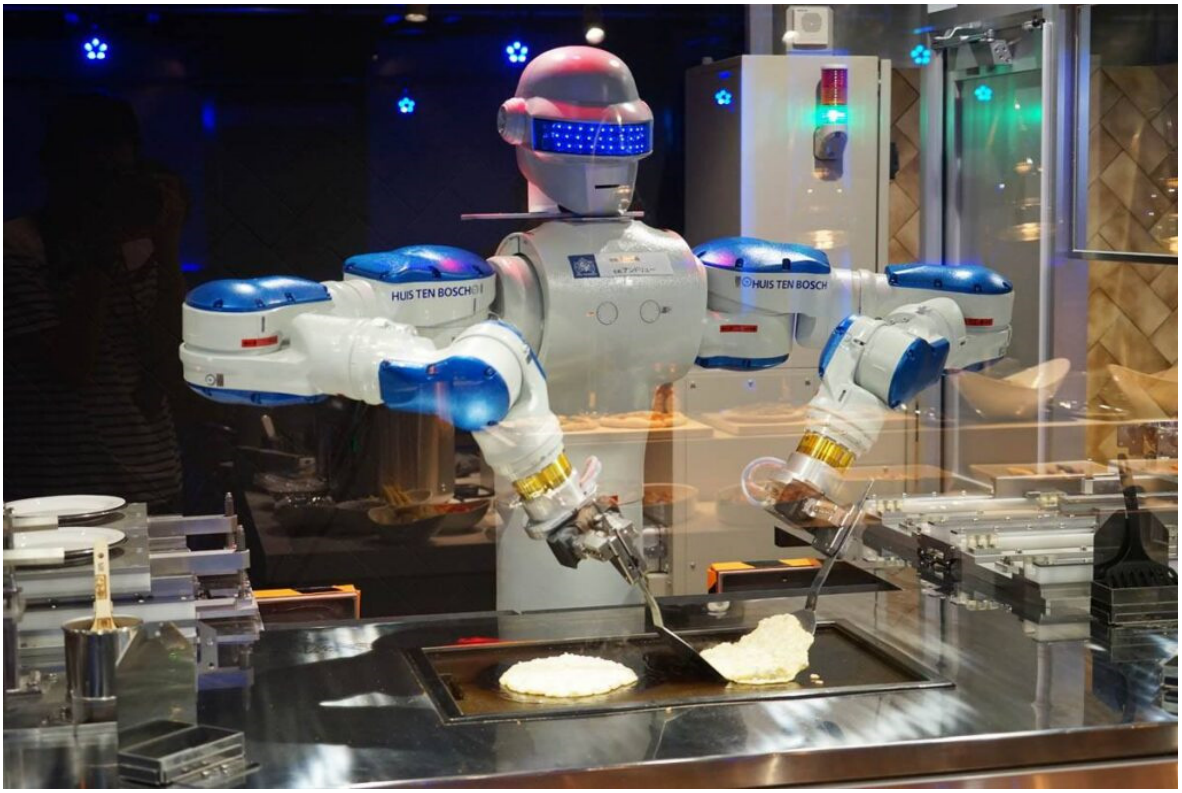


Figure 1. A chef robot preparing okonomiyaki in Japan [103].

Food safety depends on a clean and sanitized production environment. The primary disadvantage of the conventional manual disinfection method is the requirement for workforce mobilization, which raises the danger of exposure to cleaning staff. Cleaning robots, fitted with advanced sensors combined with AI-driven navigation systems, are rapidly changing the face of sanitation processes within the food manufacturing industry [104]. These will be able to make sure the space is cleaned and disinfected extensively without even needing human intervention. The development of such robots entails advancements in intelligent navigation and algorithms that can recognize high-risk, high-touch regions in addition to their disinfection capabilities [105]. Some of these cleaning robots use UV light to disinfect surfaces, adjusting their position autonomously to ensure the maximum exposure of UV light to all surfaces, effectively eliminating bacteria, viruses, and other pathogens [104]. For example, Tech-Link Healthcare Systems' autonomous UV-Disinfection Robot (UV-DR), shown in Figure 2, can disinfect and kill bacteria and viruses on all exposed surfaces by directing concentrated UV-C light onto designated infectious hotspots in hospitals or production lines. With an exposure time of ten minutes, it is estimated to kill up to 99% of bacteria including *Clostridium difficile* [106]. Our capacity to manage and stop the spread of infectious diseases can be greatly enhanced by incorporating these robots into larger preventative initiatives.

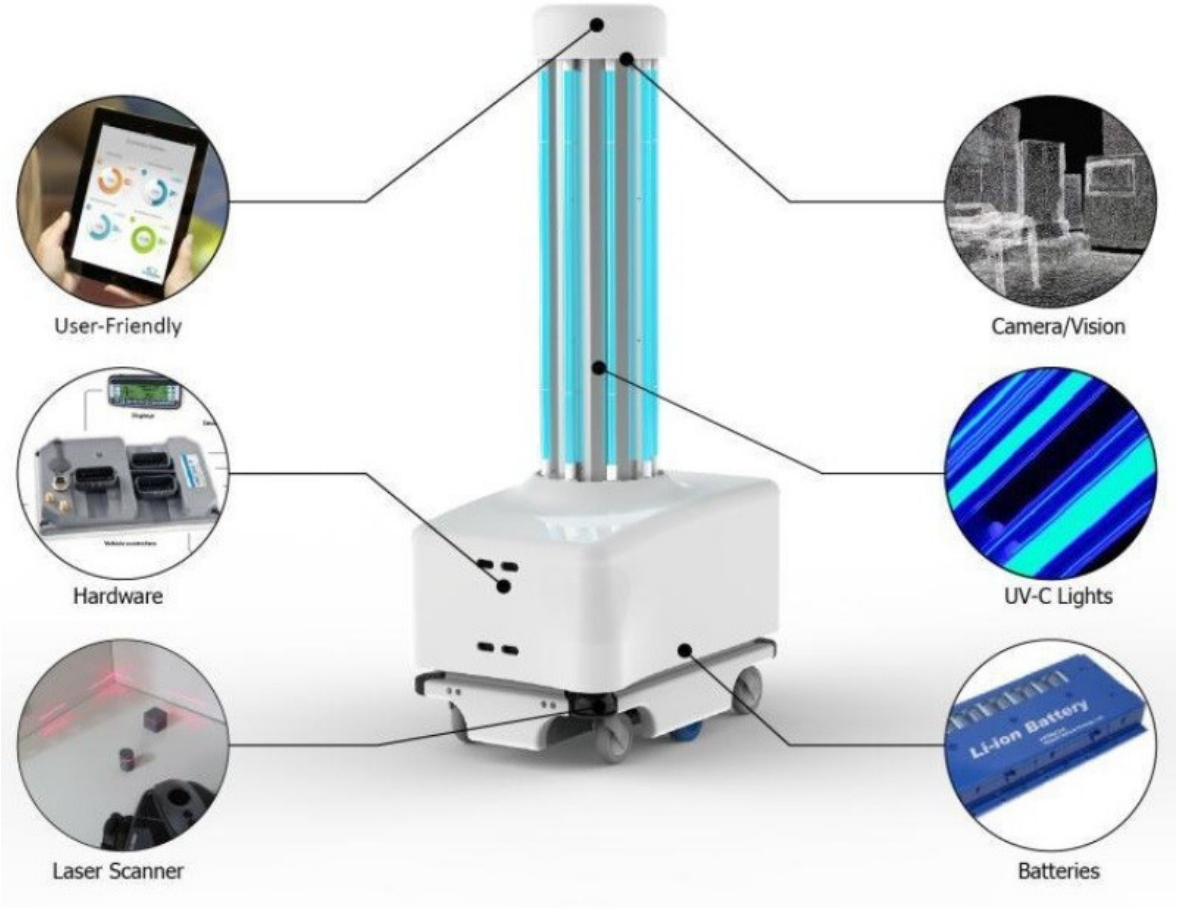


Figure 2. UV-Disinfection robot [106].

3.6. Wearable Technology (Devices for Kitchen Staff to Ensure Personal Hygiene Standards)

The food industry follows strict hygienic policies that assure food safety and quality. Key among these is hand washing, which is employed to lower the rate of illnesses and stop the spread of germs, viruses, and parasites [107]. The significance of hand washing has been further emphasized during and after the COVID-19 pandemic [108]. Wearable technology adoption for kitchen staff is one of the emerging solutions to improve hygiene compliance, including hand washing. It plays a significant role in maintaining high safety standards in the kitchen industry. These devices are worn by staff to monitor personal hygiene and ensure compliance with food safety regulations. By incorporating these technologies into the daily life of kitchen staff, one can be assured of a reduction in the risk of food contamination and overall, a safer environment.

Wearable technology in food environments often consists of smartwatches, wristbands, and badge sensors that can easily be integrated into the daily workflow of food handlers. These smart devices track, monitor, and remind workers about personal hygiene practices, especially hand washing, which is of extreme importance to minimize the risk of contamination and foodborne illness [109]. They are often equipped with sensors that can track how often a member of staff washes their hands, sending reminders if frequency falls below the accepted range, thus ensuring that personal hygiene in the kitchen is constantly met [110]. Wearable technologies also monitor other hygiene-related factors such as skin temperature and sweat levels to measure cleanliness [111,112]. For instance, the Harmony system, a hand wash monitoring and reminder system using smart watches, was developed in the study by Mondol and Stankovic [111] to assess the quality of hand washing performed by food workers. A Beacon sensor was used to send alerts when the participant was in an area that required hand hygiene or when the participant failed to properly wash their

hands. A smartwatch was worn on the participant's wrist to record movement signals, and a Bluetooth transmitter was built into the dispenser to determine whether the participant used the soap. A decision tree (DT) was used to identify hand washing classes after signals were processed to extract time-domain information. The user-independent mode was used to train the classifier. Every participant in this model is divided into two groups, and the data from one group is utilized for testing while the data from the other group is used for training. Consequently, the average accuracy of the DT classifier was 85%. The study by Zhang et al. [109] also demonstrated the feasibility of using wearable devices to detect hand washing activity and the hand washing technique as well. As shown in Figure 3, the wearable device was equipped with two Byteflies sensors, one on each wrist. The sensor includes a three-axis accelerometer and a three-axis gyroscope, each operating at 100 Hz. Each wrist's positioning direction was set and the sensors synced on their own. During the experiment, two radar sensors were also used to identify hand washing movements [109].

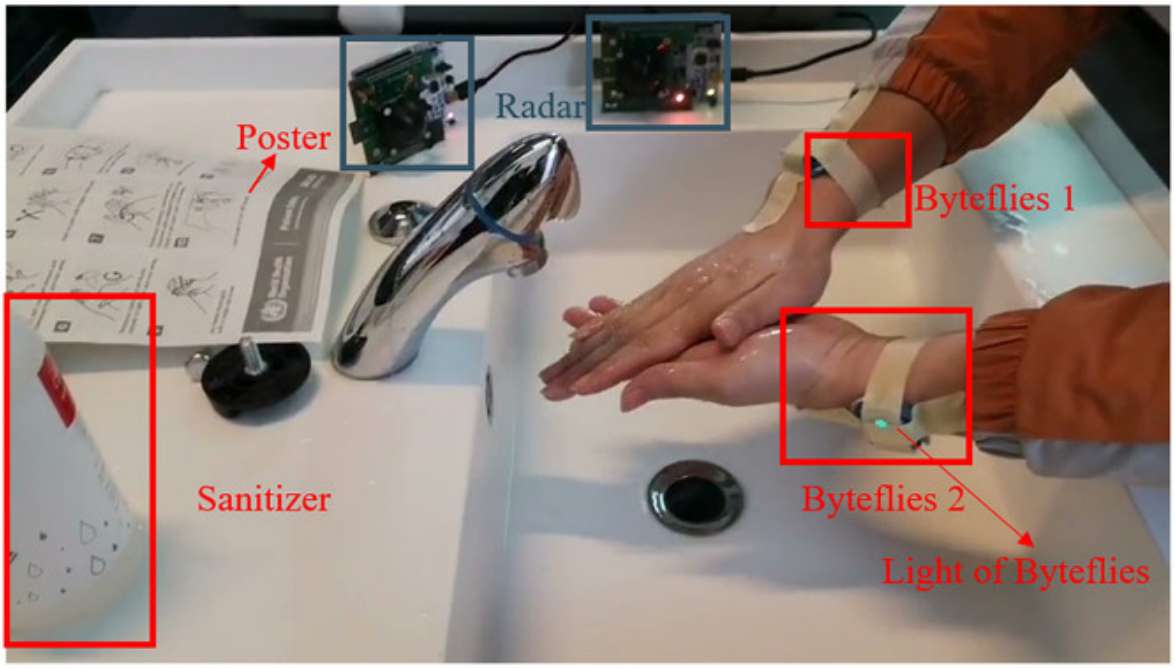


Figure 3. Wearable device with sensors for detecting hand washing activity [109].

Similarly, the use of smart gloves that can ascertain the cleanliness of the hands of food processors can aid in the maintenance of cleanliness prior to food handling, ensuring that any possible contaminations due to unsanitary hands are avoided. The addition of wearable technology in the kitchen is not only about convenience but also accountability. By equipping staff with tools that actively monitor their hygiene, staff will uphold the high standards required to ensure food safety. Furthermore, these technologies can provide data that can aid the broader understanding of staff hygiene throughout shifts [113]. However, in the introduction of wearable technology into kitchen environments, a number of factors should be considered such as comfort and ease of usability, which are key to the adoption of such devices by workers, and data privacy and employee monitoring, which need to be addressed responsibly by communicating the purpose and benefit of technology.

4. Multidimensional Impacts of Advanced Technologies on Professional Kitchens

The modern professional kitchen is undergoing a profound transformation driven by advanced technologies that enhance efficiency, ensure food safety, and optimize the use of

resources. More than just tools, these technologies support regulatory compliance while ensuring that professional kitchens meet global benchmarks set by Codex Alimentarius and the World Health Organization. Apart from the elevation of culinary performance, these advanced technologies also address environmental sustainability by reducing waste and energy consumption, improve cost-effectiveness through precise resource management, and boost customer satisfaction by ensuring consistent quality and timely service [114,115].

4.1. Operational Efficiency and Microbial Safety

The introduction of technology, AI, and automation into the professional kitchen and food industry has led to significant improvement in operational efficiency and gastronomy. One of its major impacts is a reduction in manual intervention as traditional methods of microbial safety are often labor-intensive including the collection of physical samples and culturing for microbial growth, which could take several days to produce results. These delays in identifying food safety concerns not only increase the risk of contamination but also disrupt the kitchen routine [116]. These technological advancements offer enhanced accuracy and reliability. Automations such as biosensors and rapid testing kits are capable of detecting contaminants and spoilage organisms in real time with accuracy, thereby reducing the possibility of human error [44]. These tools not only streamline monitoring but also ensure that food handling follows compliance, leading to better overall kitchen management and resource allocation [117].

4.2. Economic Considerations and Cost–Benefit Analysis

Advanced technologies in modern kitchens have notable cost implications particularly when it comes to balancing upfront technology investments with long-term savings. The initial expenses in installing automated systems are one of the major challenges for the food industry [118]. These systems are capital-intensive, including equipment purchases, installation fees, and staff training to effectively operate new tools [119]. However, despite the high upfront costs, the long-term benefits often outweigh the financial burden in terms of food safety compliance. In the long run, using these technologies by food businesses will save cost on foodborne illness outbreaks, product recalls, and compliance with safety regulations. Furthermore, automated systems lower operational costs by reducing the need for manual intervention with food and waste reduction [115].

4.3. Staff Training and Adaptation to New Technologies

In addition to the financial requirements for the integration of smart technologies in kitchens, their introduction necessitates extensive staff training to ensure successful integration, use, and management. These tools are sophisticated and so they require kitchen staff to acquire technical skill for smooth handling [120]. This shift from traditional practices to automation can be overwhelming for staff and often involves not only learning how to operate new equipment but also understanding the data these systems generate and how to apply it in daily kitchen operations [121]. Training and retraining programs are thus essential for ensuring adherence to operating protocols, reducing the risk of misusing and underutilization of these new technologies, which could lead to operational inefficiencies or compromise food safety. Importantly, to reduce the initial resistance to change or a feeling by staff of being overwhelmed, there is a need for the gradual introduction of these innovations [122]. Equipping staff with the necessary skills and confidence ensures that professional kitchens can fully realize the multidimensional benefits of these advanced technologies including operational efficiency and regulatory compliance, enhanced sustainability, cost savings, and customer satisfaction.

4.4. Consumer Confidence, Transparency, and Traceability

From a consumer perspective, the integration of smart technologies in the kitchen has significantly enhanced confidence in the safety and quality of food. In an age where customers are very conscious of the integrity and quality of the food they consume, technological innovations play a pivotal role in providing assurances that food is being prepared and served under optimal conditions [114]. Systems such as real-time microbial monitoring, temperature control devices, and biosensors adhere to strict kitchen regulations and boost consumer confidence [123]. For customers, the transparency provided by modern technology helps build trust in the restaurants they choose or other food sources. Thus, when food establishments openly share their safety protocols, customers feel safer knowing that advanced systems are in place to maintain high standards. Similarly, traceability systems such as blockchain technology allow people to see exactly where their ingredients come from, how they are handled, and how they are prepared. This level of detail resonates with the customers as they can trace the origin of the food on their plate, giving them information on not only the freshness of the food but the assurance that it has been carefully managed every step of the way, from the farm to the kitchen [124].

Some of the applications of these advanced technologies in enhancing microbial and food safety are highlighted in Table 1.

Table 1. Applications of advanced technologies in enhancing microbial and food safety.

Function/Technology	Application	AI/Robotics Contribution	Impact	References
Automated Technology	Predicting contamination risk and outbreaks	AI-driven prediction models for microbial risks	Proactive microbial management and risk prevention	[77,79]
AI in Sampling	Automating microbial sample collection	Automated data analysis for the detection of the presence of microorganisms	Enhanced data accuracy and efficiency	[85]
Metagenomics Incorporation	Analyzing microbial communities in food	AI-based analysis for microbial and genetic data	Early detection of pathogens and spoilage organisms	[125]
IoT Sensors	Environmental and microbial monitoring	Real-time predictive analytics	Proactive food safety measures	[55,61]
Robotic Sanitation	Cleaning and disinfecting food areas	Automation of sanitization routines	Reduced risk of cross-contamination	[100,104]
Allergen Detection	Monitoring recipes and raw ingredients	AI detection of potential allergens. Robots can scan raw ingredients for contamination	Improved allergen safety	[126]
Quality Control	Monitoring the quality of food	AI predicts and prevents contamination during food storage and preparation	Improved food quality	[77]
Nutritional Customization	Personalized meal preparation	AI adjusts meals to meet dietary and caloric needs	Optimized health outcomes	[127]

5. Impact on Gastronomy and Culinary Innovation

5.1. Preservation of Culinary Creativity

In recent years, the adoption of advanced technologies in commercial kitchens has significantly streamlined operations as well as enhanced the preservation and expansion of culinary creativity. One area where these technologies have had a notable impact is kitchen hygiene management. Introducing automated cleaning systems and more sophisticated cleaning agents has improved the efficiency and consistency of maintaining food safety standards in kitchens, reducing the manual workload involved in routine sanitation. These systems help create a more reliable and structured environment in which chefs and kitchen

assistants can allocate more attention to culinary tasks such as ingredient exploration, recipe development, and refining cooking techniques [128]. In addition, these advanced technologies help to reduce microbial growth on high-contact surfaces, minimize the risk of contamination, and support compliance with hygiene regulations, thereby allowing more time and attention to be allocated to food preparation and experimentation while maintaining food safety as an ongoing priority [44,129]. Thus, with the growing importance of food safety in modern gastronomy, these technologies offer the perfect balance between hygiene and kitchen innovation.

Overall, by automating routine tasks (e.g., use of automated ingredient dispensers), providing safer working conditions (e.g., use of improved ventilation systems), and enabling more efficient workflows (e.g., streamlining the order taking and fulfillment process by using order management software), these technological advances provide an environment where traditional and modern culinary practices can both thrive, thus supporting the growth of gastronomy by keeping kitchens safe, inspiring creativity, and providing the flexibility needed for innovative approaches to food preparation and presentation.

5.2. Adoption of Molecular Gastronomy

Over the years, molecular gastronomy has gained popularity and significant impact within the food science community, combining science with culinary artistry to create unique and sophisticated dining experiences. Techniques like sous vide, where ingredients are vacuum-sealed and cooked at a constant low temperature, are now commonly used to achieve dishes with better texture and flavors, or gelification, where hydrocolloids are used to create edible gels [117]. Despite the benefits, cooking methods like sous vide raise safety concerns, particularly the risk of undercooking, which can lead to foodborne illnesses [130]. To address these risks, technology has become a vital partner in the kitchen, leading to the evolution of molecular gastronomy. Approaches such as the utilization of sensors, digital thermometers, and automatic monitoring systems to provide data in real time during sous vide processing, ensuring that food stays within safe limits during prolonged cooking procedures, have become mainstream [131], leading to the creation of dishes that are both aesthetically pleasing and microbiologically safe [132]. Another important advancement is the use of technology to support creative experimentation in the kitchen such as the use of advanced tools like liquid nitrogen tanks and techniques involving emulsifiers in creating excellent dishes without interfering with safety, thereby highlighting the importance of technological involvement in gastronomy [133]. The importance of technology to the kitchen extends beyond creative applications to everyday practices, as modern professional kitchens utilize tools like digital temperature monitors, automated safety alerts, and data-driven systems to reduce human error during food preparation, which is very crucial in molecular gastronomy, where precise cooking methods must be rigorously controlled to prevent any safety lapse [134]. Some of the more commonly utilized molecular gastronomy approaches are highlighted in Table 2.

These commonly utilized molecular gastronomy techniques, as highlighted in Table 2, have transformed the dining experience, making it possible to create visually appealing dishes, boosting both creativity and safety in restaurants that use molecular gastronomy [130].

Table 2. Key techniques in molecular gastronomy and their culinary applications in the modern kitchen.

Molecular Gastronomy Techniques	Description	Culinary Application	References
Emulsification	Combining two immiscible liquids, such as oil and water, using emulsifiers such as lecithin.	Results in foams or creamy textures that are light and airy, often used in sauces or garnishes to add an airy feel without heavy creams, e.g., foamed oils or liquid-based sauces.	[135,136]
Spherification	A process where liquids are transformed into flavorful spheres that burst in the mouth using sodium alginate.	Creates caviar-like spheres, widely used in avant-garde dishes to add a unique texture and a burst of liquid flavor, e.g., balsamic vinegar pearls or fruit caviars.	[137,138]
Gelification	The use of gelling agents like agar-agar or gelatin to create firm textures from liquids.	Allows chefs to produce gels from almost any liquid, providing a wide variety of textures for both savory and dessert dishes, e.g., gelled olive oil or fruit-based gels.	[136,139]
Flash Freezing (Cryogenic Cooking)	Rapid freezing of ingredients using liquid nitrogen to create crisp texture and unique presentation methods.	Enhances texture by flash freezing liquids or solids, resulting in novel textures in food, e.g., frozen fruit powders or shattering frozen elements in desserts.	[140,141]
Foaming and Aeration	Using chemical agents like soy lecithin to create stable foams.	Adds visual appeal and unique textures to dishes, often used to top desserts, soups, or beverages, e.g., coffee or fruit foams that add flavor without heaviness.	[133]

5.3. Food Sustainability and Waste Reduction

Food waste has become a global challenge, with far-reaching implications for sustainability, food security, and environmental health [142]. The culinary industry, which often deals with high volumes of perishable goods, is in a good position to address this challenge. Recent advances in microbial management, particularly through techniques such as fermentation, biopreservation, and the use of probiotics, are vital in reducing food waste [143]. In modern professional kitchens, these microbial techniques are increasingly integrated with smart technologies for better outcomes, for example, fermentation monitoring systems equipped with IoT sensors that track pH, temperature, and microbial activity in real time [56], or AI-based spoilage detection devices that alert chefs when ingredients approach unsafe microbial thresholds [144]. This integration ensures that preservation processes remain within optimal parameters, extending the shelf life and reducing spoilage without sacrificing quality.

According to Uehara et al. [145], microbial processes such as food fermentation, which have been shown to extend the shelf life of food products, can be enhanced by automation. This process is supported by IoT technologies, which streamline production, aid in minimizing human error, and ensure consistent product quality. Consequently, sensors can continuously measure key parameters such as temperature, humidity, and acidity at multiple stages of the process, with data transmitted in real time to servers, computers, or cloud storage for remote monitoring and control [146]. These measurements can be analyzed during fermentation and displayed through web or mobile applications, enabling timely adjustments that prevent the quality degradation of the final product [147]. Recent innovations demonstrated by Zhang et al. [148] show that stretchable strain sensors made from starch blended with the conductive polymer poly(3,4-ethylenedioxythiophene): polystyrenesulfonate (PEDOT:PSS) can track real-time volume changes in starch-based foods during processes such as fermentation, steaming, storage, and refreshing. These sensors detect expansion and shrinkage patterns, enabling precise control over processing conditions to maintain consistent quality and improve productivity while reducing energy

use. When integrated with IoT systems, this technology offers professional kitchens a powerful tool for monitoring and optimizing production in real time.

5.4. Enhanced Dining Experiences

The incorporation of technology in restaurants is reshaping how customers view cleanliness and food quality. Studies have shown that when customers see the use of technology in restaurants, it gives them more confidence that the food is clean and safe, which in turn impacts their trust and satisfaction as customers are more accepting of these technologies when they enhance hygiene and food quality [149]. This is most applicable to digital tools like automated cleaning systems and real-time temperature monitoring, which significantly improves customer perceptions of a restaurant's hygiene [150]. In a recent study evaluating smart technologies such as touchless payment systems and robotic cleaning devices, these innovations have been shown to influence customer expectations of cleanliness in a facility [151], which in turn increases clientele. In a study on AI-driven cooking processes and real-time kitchen monitoring, it was found that customers appreciated transparency, with real-time monitoring boosting confidence about the safety and quality of the food [152]. Apart from this, flexibility contributed by such technologies helps the handlers to meet the rising demands for dietary varieties with ease without compromising operational efficiency [24,87]. Automation ensures that culinary processes such as the tracking of inventory ingredients to alterations in recipes are performed efficiently without hassle. Overall, the instant analysis of food products enabled by advanced AI and sensor technologies ensures that contaminants are identified promptly, and customers with dietary restrictions are protected, including those suffering from severe allergies [126].

6. Challenges and Limitations

The introduction of modern technologies for monitoring microbial safety in professional kitchens has undoubtedly improved food safety practices. However, their implementation is not without notable challenges and limitations. These challenges and limitations are discussed below.

6.1. Financial Constraints

One of the hindrances to the implementation of these technologies is the high cost involved. Cost poses a major setback especially for small-scale kitchens and independent establishments. While large-scale kitchens can afford the cost of real-time microbial monitoring systems and automated hygiene tools, smaller establishments struggle. This gap creates an uneven playing field, where smaller kitchens often rely on traditional, less technologically advanced methods. While these approaches can still maintain high safety standards when applied rigorously, limited access to advanced, more precise tools may reduce consistency in monitoring and increase the risk of lapses in some cases [153]. For instance, PizzaGo, a regional pizza chain, implemented an AI-powered food quality inspection system that integrates cameras and sensors at supplier sites and in-store, along with predictive analytics to monitor ingredients, toppings, and finished pizzas for potential safety issues [154]. The system enabled PizzaGo to achieve a 60% reduction in food safety risks, an 85% drop in food quality-related complaints, and cost savings through waste reduction and fewer recalls. However, they faced notable challenges including high initial investment in AI-capable cameras, software, integration into existing systems, and maintaining the new technology; complex integration that required backend and operational system updates; and staff training demands [154]. These challenges demonstrate how the upfront financial and operational burdens can delay or limit the adoption of these tech-

nologies even when the Return on Investment (ROI) is favorable, particularly for smaller establishments with lean budgets and limited technical support.

6.2. Technical Limitations and Reliability Issues

In addition to financial concerns, technical reliability is another significant limitation. Advanced systems offer precision in monitoring microbial contamination, but they are not immune to malfunctions, calibration issues, or false positives. These technical failures can lead to unnecessary alarms and missed contamination risks. Therefore, managing these systems requires trained personnel, which sometimes is a challenge, especially in kitchens that are demanding and the technical expertise of staff is limited [153]. This unreliability, combined with the need to constantly maintain the equipment, could lead some kitchens to revert to manual monitoring methods despite the potential benefits of technological solutions. Moreover, the effective integration of various data sources used for the training and deployment of AI models including data from microbiological samples; sensor data from IoT devices continuously monitoring the temperature, humidity, gas levels, etc., in the storage and processing environment; and data from the environmental conditions such as storage conditions or supply chain variances poses a great challenge [77,85,86]. This is majorly because the diversity and size of these data sources beget complexity, since they need harmonization and structuring into formats that the AI models can compute and analyze efficiently [155]. There is also the risk of bias if these AI models are trained on imbalanced or flawed datasets. Hence, rigorous testing and continuous monitoring of the AI algorithms should be considered to ensure fairness and accuracy within food safety predictions.

6.3. Workforce and Operational Disruptions

In kitchens with high turnover, maintaining the consistent use of the technology becomes even more challenging [156]. Integrating new technologies into kitchens with established workflows can be disruptive. Kitchens often operate under tight schedules, and introducing advanced monitoring systems may require significant changes to existing processes and could ultimately affect the business. Proper integration requires retraining staff and adjusting routines, which can be time-consuming and costly, and if not done well can impact the business. It is worthwhile noting that there is a risk of over-reliance on technology, which can lead to kitchen staff paying less attention to important food safety practices. While automated systems provide an added layer of precision, they cannot entirely replace intuition and attention to details that humans bring to the table. For example, physical checks such as visually assessing food for spoilage or contamination remain vital to ensuring food quality and can only be performed by humans. If staff become overly dependent on technology, the absence of regular manual checks could increase and so will the risk of microbial contamination [157]. Therefore, balancing the use of technology with traditional safety practices must occur concurrently for maintaining high food safety standards.

6.4. Regulatory and Compliance Challenges

From a regulatory perspective, the rapid advancement of microbial safety technologies often outpaces the development of regulatory frameworks to keep them in check. This lag can create uncertainty for kitchens as it relates to compliance and the acceptance of new technologies. Also, the lack of standardized protocols for using and evaluating these technologies can result in inconsistent practices that make it difficult to measure effectiveness across various businesses [158]. One kitchen might adopt a proprietary biosensor and apply an internal validation method, while another might use a different detection threshold. Such inconsistencies make it difficult to establish industry-wide benchmarks

for accuracy, sensitivity, and reliability. This lack of harmonization hampers the cross-comparison of results and complicates the ability of regulators, auditors, and certification bodies to consistently measure the effectiveness of these technologies across different operations. Furthermore, in a situation where a system could not detect contamination due to differences in calibration or software failure, determining whether the manufacturer, the kitchen operator, or the regulatory body takes responsibility can be legally challenging. In the absence of clear guidelines, such ambiguity may deter investment in these advanced microbial monitoring technologies, particularly for small professional kitchens that lack the capacity to afford the potential legal charges.

6.5. Ethical and Social Implications

Advanced kitchen monitoring systems, including AI and IoT-enabled systems, can collect large amounts of sensitive data, such as information about suppliers, production schedules, and operational insights, which could be exploited if accessed by competitors or unauthorized parties. Data breaches that could occur through cyberattacks, inadequate encryption, or internal mishandling could expose confidential supplier contracts or operational vulnerabilities, causing financial and reputational harm [159]. Ethical issues may arise when personal data collection such as worker activities or customer purchase patterns happens without consent or proper protection [160]. Hence, deploying these technologies ethically in kitchens requires full transparency about what data is collected, how it will be used, and who will have access to it. For instance, if staff performance metrics or customer purchase patterns are being monitored, their consent should be obtained in compliance with local and international data protection regulations such as General Data Protection Regulation (GDPR) [161]. Policies should also be communicated clearly to all stakeholders involved, and anonymization techniques should be applied where possible to safeguard personal identity. Trust between management, employees, and clients could be damaged if informed permission and appropriate governance over data use are not guaranteed.

Furthermore, increased automation within professional kitchens can reduce the need for repetitive, manual kitchen tasks such as temperature checks, cleaning cycles, or stock monitoring [162]. While this can enhance operational efficiency, it could also displace jobs, which raises concerns about the welfare of workers. Hence, in shifting kitchen processes to automation, proactive workforce planning should be considered that includes retraining and upskilling programs to help displaced workers transition into new roles that are relevant for automation processes such as technology maintenance, quality control, or data analysis to maintain a decent level of equality within professional kitchens.

6.6. Emerging Microbial Threats

Finally, the ever-evolving nature of microbial threats makes the use of technological tools for microbial monitoring more complex. New strains of pathogens continue to emerge due to continuous genetic variation, horizontal gene transfer, and environmental adaptation [5]. Hence, monitoring systems must adapt to detect these threats effectively. However, a delay in updating current systems to address these new threats and the time it takes regulatory bodies to approve new protocols may create a challenge [153,163].

7. Future Trends

The future of keeping food safe using microbial methods is being reshaped by a wave of these new technologies. These technologies offer new ways of reducing contamination risks and improving hygiene. AI-driven systems can predict potential contamination patterns using large amounts of data, while robotics help automate food prep and cleaning processes, thus providing more accuracy and reducing human errors [164]. There is room

for improvement in these technologies as they can be better adapted to ensure proactive measures are taken before contamination issues escalate. The use of AI and blockchain technologies to accurately forecast contamination risk ahead of time is still an emerging field that needs focused research [165,166]. By leveraging these tools, professional kitchens can enhance safety as well as reduce food wastage. Personalized safety protocols could be developed based on individual health profiles, including microbiome data. This could be further enhanced by wearable technology that monitors food safety in real time, helping individuals avoid harmful microorganisms or allergens that pose unique risks to them [115]. Such advancements would enable kitchens to cater to diverse populations, ensuring food safety at both the macro and individual levels.

Additionally, technologies like blockchain and the Internet of Things (IoT) are enhancing supply chain transparency and microbial safety. Because blockchain offers a secure, decentralized way of tracking food from its source to the kitchen, reducing the chances of contamination during transportation, the system can be adapted to enhance food traceability and tackle the growing incidences of food fraud. This is important as food fraud is a growing challenge in several emerging global markets especially in Africa and South East Asia [167,168]. Similarly, regulatory agencies can utilize IoT sensors with their monitoring and instant data analysis systems, incorporating these into food hygiene rating systems to monitor compliance to standards by kitchens. This level of visibility will help ensure that kitchens maintain high standards of safety throughout the entire food preparation process. Finally, virtual and augmented reality (VR and AR) are changing the way food safety training works by allowing kitchen staff to practice identifying and handling contamination in realistic scenarios. Augmented reality systems can give real-time feedback, pointing out to kitchen staff areas that need cleaning or extra attention. These interactive tools will make it easier to reinforce food safety standards and ensure the same practices across the kitchen [169] and thus require further research attention. Similarly, adoption strategies for kitchen staff should feature retraining and upskilling programs that prepare them for newer roles that will complement automated systems.

Big data and cloud computing have a critical role in food safety management. Bringing together data from sensors, monitoring devices, and predictive tools enables cloud-based platforms to give centralized control over safety protocols and this ensures real-time adjustments to microbial safety measures and provides valuable insights to prevent contamination outbreaks [75]. As these technologies continue to change, they will not only improve food safety but also define the standards of cleanliness and efficiency in the food industry.

Importantly, the successful integration of these emerging technologies will also be highly reliant on the establishment and streamlining of local and international regulatory frameworks. National food safety authorities and institutions such as the Codex Alimentarius Commission and Food and Agriculture Organization have significant roles to play in defining the validation needs of microbial detection systems, compliance requirements of risk forecasting with AI, and standards for blockchain traceability. In nations with stringent data protection legislation such as the European Union's General Data Protection Regulation (GDPR), IoT, and AI systems' implementation must also meet stringent privacy and transparency standards that may influence system design and data governance strategies [161]. Furthermore, international supply chains may also be affected by differences in country legislation, in areas such as specific hygiene verification procedures or the outright restriction of the use of unapproved biosensors. Consequently, the pace of technology adoption is typically constrained not only by technical readiness but also by the speed with which regulatory bodies can modify their frameworks to accommodate new capabilities and safeguard public health, labor rights, and data integrity.

8. Conclusions

The evolution of technology has drastically transformed professional kitchens, providing tools and systems that enhance efficiency, improve food safety, and contribute to sustainability. These advancements, spanning from automation to real-time microbial monitoring, are reshaping both the operations of kitchens and the overall dining experience. In this article, we have explored the major technological innovations that have impacted the culinary world, including their implications for kitchen operations, training needs, food safety, and sustainability. These technological advances in modern kitchens have undoubtedly transformed the culinary landscape, offering significant improvements in operational efficiency, food safety, staff training, and sustainability. Innovations like automation, IoT, AI, and precision cooking technologies have streamlined kitchen operations, whilst enhancing food safety and reducing waste. While the initial investment in these technologies can be high, their long-term benefits, especially in terms of cost savings and sustainability, make them valuable assets for professional kitchens. As technology continues to evolve, the culinary industry will likely see even greater opportunities for innovation, creativity, and sustainability in the years to come. For the seamless adoption of these technologies and for the assurance of food safety monitoring in professional kitchens, there is a need for the continuous evaluation of the safety features and user-friendliness of these technologies, with further emphasis on their affordability and sustainability to ensure widespread uptake and integration. Ultimately, close collaboration between technology developers, food professionals, and policymakers will be essential to overcome current limitations, align innovations with real-world kitchen needs, and ensure that regulatory frameworks keep pace with technological progress.

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