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Review Article

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Biosensors for Food Spoilage Detection: A Comprehensive Review of Current Advances

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Abstract

Food spoilage is an enormous problem in the food industry because it can result not only in wastage of food and financial losses but can also lead to health-related problems. Therefore, a timely identification of food deterioration is essential and can greatly help ensure food safety, minimize financial losses, and maintain consumer confidence. In recent years, biosensors have evolved into a rapid, sensitive, and highly reliable methods for detection of food spoilage indicators. Biosensors are composed of unique biological detection elements and transducer elements that enable the quantification of food spoilage markers like volatile organic gases, microorganisms, or enzymes. This review article discusses the principles, types, and sensing mechanisms of biosensors used in this field, highlighting their advantages and limitations. The article also addresses the factors responsible for spoilage of food which could be detected by that biosensor, such as microbial activity, enzymatic processes, and metabolite synthesis. Furthermore, it presents the most recent advancements in signal transduction techniques, identification components, and sensing platforms used in food spoilage biosensors. Overall, the review objectively evaluates the current state of biosensors in terms of sensitivity, selectivity, and applicability to different food samples and highlights the challenges and prospects in the field of biosensors, including the application of nanotechnology, miniaturization, and data processing methods for improved prediction.

Keywords

Food spoilage, Biosensors, Nanotechnology, Sensitivity, Selectivity, Food safety

Introduction

Food spoilage refers to the deterioration of food quality and safety, making it unsafe to consume owing to variations in flavor, texture, odor, appearance, or the development of dangerous microbes. Spoilage of food is a widespread issue that has an impact on both consumer health and the food industry's financial sustainability [1]. A timely and precise identification of food deterioration is essential and can greatly help ensure food safety, minimize financial losses, and maintain consumer confidence. Traditional methods for detecting spoilage, including as sensory assessment and microbial culture-based approaches, these methods are time consuming and have limited sensitivity [2]. In recent years, biosensors have evolved into a rapid, sensitive, and highly reliable methods for detection of food spoilage indicators.

Biosensors are composed of unique biological detection elements and transducer elements that enable the detection and quantification of markers related to food spoilage. The biological detection elements in biosensors could be enzymes,

antibodies, DNA, or aptamers, which selectively interact with target analytes associated with food spoilage. The transducer elements convert the detection event into a measurable signal. The integration of biological components with advanced sensing technologies provides significant benefits for food spoilage detection like high sensitivity and specificity, and real-time monitoring [3-6]. This comprehensive review aims to deliver a thorough and up-to-date overview of current advances in biosensors for food spoilage detection. It will delve into the factors that affect food spoilage followed by principles and mechanisms underlying different biosensor types used in food spoilage detection. With an emphasis on contemporary breakthroughs in sensor design, and integration into portable devices and smart packaging, it covers a variety of biosensor types and their applications.

Biological recognition elements that can specifically bind to the target analyte makes the backbone of a biosensor and determines its specificity. Enzyme based biosensors employ specific enzymes to catalyse reactions with spoilage indicators and produce detectable signals. Such biosensors have been effectively utilized to identify chemicals related to spoiling processes, including histamine [7, 8] biogenic amines [9, 10], and volatile organic compounds. Genetically modified microorganism has also been used as sensing components in biosensors to identify gases, metabolites, or biomarkers generated by microbes that cause rotting [11, 12]. Immunological biosensors have made a special niche for themselves in the field of spoilage detection because They can be incorporated into user-friendly platforms such as immunochromatographic strips and lateral flow devices, enabling on-site and rapid spoilage detection [13]. These sensors utilize the superior affinity and high specificity of antibodies for antigens or chemicals indicative of food spoilage [14, 15]. DNA-based biosensors identify their analyte using highly specific hybridization reaction between the probe and spoilage related targets [16]. Synthetic oligonucleotides with a high affinity and selectivity for target molecules are also used in biosensors. These oligonucleotides are called aptamers and can be created to identify chemicals that contribute to spoilage, such as proteins, toxins, and other small molecules [17-20]. The utilization of nanomaterials for fabrication of biosensors has significantly enhanced their performance. To increase the sensitivity, signal transduction, and target capture capabilities, nanomaterials like carbon nanotubes, quantum dots, gold nanoparticles, and magnetic nanoparticles have been extensively investigated. Such biosensors also called as nano-biosensors show considerable potential for ultrasensitive and multiplexed detection of spoilage indicators facilitating early and accurate spoiling monitoring [21-23].

This review will focus on different factors that are responsible for spoilage of food and how these factors are targeted for detection using biosensors. It will provide insights into the current state of biosensors for food spoilage detection, their principles, advantages, application, and limitations followed by a comprehensive discussion about the recent advances that have been brought upon by utilization of nanomaterials, machine learning and artificial intelligence, microfluidic technology, and smartphones.

Factors affecting food spoilage

Understanding of factors that affect food spoilage is essential for developing effective strategies to prevent or minimize it. The rotting process is influenced by a variety of interrelated factors, including internal and extrinsic characteristics (Figure 1). The intrinsic properties such as its composition, pH, water activity, nutrient content, and natural antimicrobial properties are inherent to the food itself [24]. All these factors can create a conducive environment for microbial growth or some enzymatic reactions that can lead to spoilage of food. On the other hand, extrinsic factors are outside variables like temperature, humidity, packing, storage conditions, and handling techniques that have an impact on the food during production, shipping, storage, and handling. A proper management of these factors is necessary to prevent or delay the food spoilage and decrease the risk of microbial contamination.

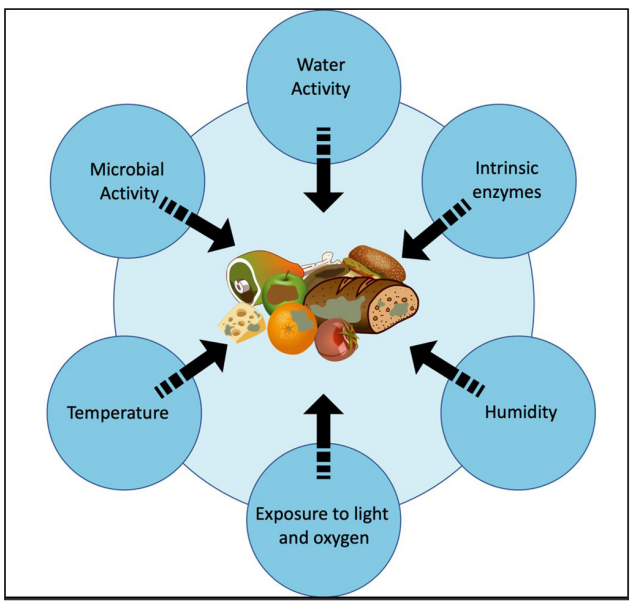

Figure 1: Factors that affect food spoilage.

Intrinsic factors

Composition

Susceptibility of a food to deteriorate is influenced by its moisture content, nutritional composition, pH level, and presence of natural antibacterial agents like carvacrol, vanillin, allicin, cinnamic aldehyde, etc. [25]. While certain microbes are restricted by acidic or alkaline conditions, others may thrive nutrient-rich habitats.

Water activity

Water activity refers to the amount of water present in a food and is a key factor in microbial proliferation leading to food degradation. High water activity promotes microbial growth and low water activity prevents it.

Extrinsic factors

Temperature

One of the most important external elements impacting food decomposition is temperature. Microbial growth is sup-

ported at higher temperatures; therefore, the increased temperatures have the potential to hasten degradation by accelerating microbial growth and enzymatic activities. Inadequate temperature control during transportation or storage can significantly reduce the shelf life of perishable food.

Exposure to light and oxygen

Aerobic microbes can easily proliferate in presence of oxygen, which can also speed up oxidative processes that lower the nutritional value of food and cause unpleasant tastes. Similarly, the ultraviolet light can also trigger certain chemical reactions in food causing unwanted change in color or taste of the food. Proper packing methods, such as vacuum packaging in opaque containers can reduce the light and oxygen exposure.

Humidity

Water content is an important factor for microbial growth. High humidity can foster the growth of mold and yeast, causing food to deteriorate. Additionally, it can lead to moisture migration, which can alter the texture of the meal.

Microorganisms

Growth of microbes like bacteria, yeasts, and molds in food is one of the most common causes of food spoilage. Microbial growth is affected by the temperature, water activity, pH, oxygen availability, and the amount of nutrients in the food [26]. Microorganisms can release some enzymes that catalyse chemical reactions, leading to changes in flavor, color, texture, and nutrient composition. Enzymatic reactions can result in protein breakdown, lipid oxidation, enzymatic browning, and other events that are associated to spoilage. Some microorganisms like *Clostridium botulinum*, *Staphylococcus aureus*, *Bacillus cereus*, *Aspergillus flavus,* etc., can also release toxins that are highly dangerous for human health if consumed.

Enzymatic reactions

Most foods naturally contain enzymes, or they can also be produced by microbial growth in the food. Enzymes can catalyse various chemical reactions in the food leading to various changes in food quality, like texture degradation, flavor changes, color fading, and nutrient loss. Common examples of such enzymes are proteases, amylases, oxidases, and lipases. Proteases digest proteins into smaller peptides. Excessive protease activity can lead to the degradation of protein-based structures, causing texture changes and off-flavors. The function of lipases is to hydrolyse lipids into fatty acids and glycerol. Lipase activity is the major reason behind rancidity, bad smell and change in texture of food. Amylases are responsible for converting complex carbohydrates into simpler sugars like glucose or fructose. Amylase activity can lead to the breakdown of starch in fruits and vegetables, causing softening of texture and development of a sweet flavor. Oxidases catalyse the oxidation of chemical compounds present in food leading to change in its color or taste. For example, polyphenol oxidase causes enzymatic browning in fruits and vegetables, leading to undesirable color changes.

Storage and handling

The length of time food is stored or handled before consumption, its cross contamination during storage or transport, and hygiene practices greatly impact its shelf life. While the extended storage can increase the risk of spoilage microorganisms proliferating, improper handling practices, like inadequate sanitization of food contact surfaces and equipment, can lead to cross-contamination. The introduction of spoilage germs during food processing, preparation, and handling must be avoided by practicing good personal hygiene and sound manufacturing processes.

Biosensors for detection of food spoilage

Biosensors play a crucial role in ensuring food safety and quality and use of biosensors could greatly affect the food industry by increasing the shelf life of food. These cutting-edge tools integrate biological identification components coupled with transducers to detect the signs of spoilage in samples. They offer quick, sensitive, and highly specific detection, enabling prompt action, reducing the chances of spoiled or contaminated food. Biological recognition element is the most important part of a biosensor. The choice of the recognition element is determined by the precise spoilage signal being recognized. For instance, microbial biosensors utilize antibodies, enzymes, or DNA probes to pick out and identify bacteria that cause deterioration. While chemical biosensors look for chemicals or metabolites connected to spoiling processes.

Compared to the more conventional techniques, these biosensors provide several benefits for detecting food deterioration because they generally need very less sample preparation, and are portable, and inexpensive. Biosensors provide near real-time monitoring, enabling rapid evaluation of food quality and freshness. Moreover, they may be integrated into the different phases of the food supply chain, like manufacturing, processing, storage, and distribution, allowing for continuous monitoring and quality control. Based on their target analyte these biosensors can be categorized into following categories:

Enzymatic biosensors

The purpose of enzymatic biosensors is to identify enzyme activity as a symptom of food deterioration. These biosensors use enzymes in their recognition elements to specifically interact with spoilage-related enzymes. Proteases, lipases, and amylases, which are generated by spoilage bacteria or released during food breakdown processes, can be detected using enzymatic biosensors.

Microbial biosensors

These biosensors are designed to identify microorganisms present in food. In their recognition element they utilize specific microbial identification components like antibodies, enzymes, or DNA probes, to target and find the spoilage-causing microbes. These types of biosensors can detect spoilage-causing bacteria, yeasts, and molds at very low numbers allowing timely intervention.

Chemical biosensors

Chemical biosensors are used to detect specific metabolites or chemical compounds that are commonly associated with food spoilage. To specifically capture and detect mole-

cules associated with spoilage, these biosensors utilize several types of chemical recognition elements in their recognition element, such as antibodies, aptamers, or receptors. Chemical biosensors are used for detection of harmful chemicals in food like toxins and allergens. These sensors are also used to identify the presence gases produced by bacteria that cause deterioration. For instance, because of enzymatic reactions during spoilage, various gases are created, such as ammonia, sulfur compounds, or volatile organic compounds (VOCs).

Optical biosensors

Changes in optical characteristics of food are targeted by optical biosensors to identify food deterioration. They can measure aspects of food samples such color changes, turbidity, fluorescence, or absorbance. Optical biosensors may identify signs of food deterioration such as oxidation, protein denaturation, or the presence of microbial metabolites that modify the food's optical characteristics.

Electrochemical biosensors

Electrochemical biosensors focus on changes in electrical signals or other attributes brought upon by processes associated with food. They transform biological interactions into electrical impulses using electrodes and transducers. Electrochemical biosensors may identify some initial signs of food spoilage such as pH changes, redox reactions, or the release of certain ions.

Recent advances in food spoilage biosensors

Last few decades have witnessed significant advances in the field of material science, electronics and processing, and machine learning. Developments in the field of nanotechnology made it possible to create nanostructured biosensors, which have better detection limits and quicker reaction times. The integration of biosensors with smartphones and other microfluidic smart devices has also advanced significantly, allowing for real-time data monitoring and analysis. Below we describe the most impactful improvements in the field of biosensors that have enabled faster, more accurate, and more cost-effective methods for identifying spoiled or contaminated food.

Nanomaterial-based biosensors

Nanoscale materials, such nanoparticles, nanowires, or nanocomposites, are used in nanomaterial-based biosensors to improve their sensitivity and effectiveness [27]. Nanomaterials provide a combination of several novel properties like large surface area, high electrical and thermal conductivity, and improved optical properties that are highly desired for manufacturing of biosensors [28]. To specifically captures signatures of spoilage, these nanomaterials can be functionalized with recognition components like enzymes, antibodies, or aptamers. Optical, electrochemical, or mass-sensitive transduction techniques are just a few of the transduction methods that may be used to detect the interaction between the target analyte and the nanomaterials. Real-time monitoring of food spoiling signs is made possible by the integration of biosensors into a variety of forms, such as portable devices, lab-on-a-chip (LoC) systems, or smart packaging.

Integration of biosensors in smart packaging

Recent developments in material sciences have enabled the development of multifunctional sensor systems that can be embedded inside the packaging itself [28]. Typically, these smart packaging keep tabs on the temperature, gases, humidity, and microbial presence in the food [29, 30]. One of the examples of such smart packaging materials is polydiacetylene (PDA) which have gained significant attention in recent years for the detection of food spoilage. PDAs are conjugated polymers that have the unique ability to change color in response to certain stimuli. They have a distinctive blue hue in their unstimulated condition, which changes to red or some other colour when exposed to outside influences. PDAs are ideally suited for the creation of sensor platforms that can visually identify signs of food spoilage because of this characteristic. The basic working principle of PDA-based biosensors is the interaction of the analyte of interest, such as spoilage-related microbes, enzymes, or metabolites, with the PDA matrix [31, 32]. Upon interaction the PDA backbone undergoes molecular rearrangements that modify the conjugation length and therefore the color of the PDA sensor [33]. Sensors made of PDA provide several benefits for detecting food deterioration. They offer a simple visual or spectroscopic readout and are well suited for integration into other sensor systems because to their outstanding stability, sensitivity, and compatibility with diverse substrates [34].

Internet of Things (IoT) and wireless technology

Integration of biosensors with IoT technology enables continuous and real-time data monitoring [35]. The wireless connectivity allows for remote monitoring of food spoilage and efficient quality control throughout the food supply chain [36]. These biosensors are capable of monitoring multiple variables like pH levels, humidity, ethylene and ammonia concentrations, and temperature in real-time. Through the IoT network, data gathered by the sensors is sent to a central system. This data may be processed using sophisticated analytic techniques to reveal patterns and trends. These insights could prove to be highly beneficial in improving the storage conditions, transportation logistics, and streamlining the production process [37].

Machine learning and artificial intelligence (AI) based data analytics

Advanced data analytics techniques, such as machine learning and AI, have been applied to biosensor data [38] for food spoilage detection. These algorithms can process large datasets that are populated by IoT based biosensors, identify patterns, and make predictions about the quality and safety of food products [39]. AI based algorithms can trained to recognize patterns in the data from different types of sensors [40]. This sensor fusion allows machine learning algorithms to categorize food samples as fresh, somewhat ruined, or substantially spoilt based on the biosensor readings by studying historical data on the evolution of spoiling [41]. Moreover, by combining biosensor data with other relevant information, such as environmental conditions and transportation parameters,

predictive models can be built [42]. Such models can predict when a food product is likely to reach an unacceptable degree of spoiling by accounting for the dynamic changes in spoilage indicators [43]. These forecasts could prove to be highly useful for managing inventories and cutting down on food wastage.

LoC devices

LOC devices contain microfluidic systems that can integrate various functions, including sample preparation, target detection, and analysis, into a single platform (Figure 2). These devices that have gained immense attention in biosensing applications due to its ability to handle small sample volumes [44]. By tracking numerous variables like pH, temperature, biogenic amines, and volatile gas emissions, LoC devices can assess the overall quality of food using only a few microliters of samples [45]. These devices often come in form of disposable cartridges or chips and connect to smartphone interfaces for performing assays and providing quantitative results.

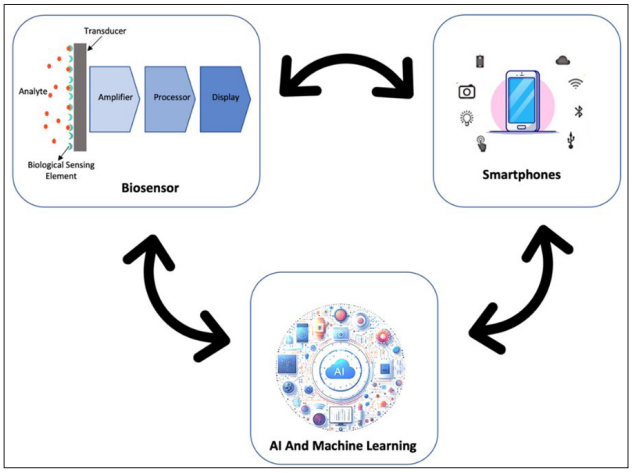

Figure 2: Recent advances in biosensor field involve integration of loc system with internet of things using mobile platforms like smartphones which offer excellent connectivity and processing capabilities. AI and machine learning tools can help optimize various processes in the food industry by real time monitoring of biosensor data.

Smartphone based biosensing

Smartphone-based biosensing platforms have gained popularity due to being economical and highly accessible. Smartphones may be converted into miniature biosensors using portable add-ons or accessories, allowing for quick on-site testing [46]. These devices use the integrated sensors to identify the signatures of food spoilage integrated using the computing power of smartphones. The biggest advantage of smartphones is that they offer extensive connectivity options, such as Wi-Fi, Bluetooth, or cellular networks, and sufficient processing power to permit data exchange and real-time monitoring. This allows biosensors to process and send the results to a centralized database, allowing for real-time remote monitoring, data analysis, and decision-making [47]. Another advantage of smartphone-based biosensors is that they are ubiquitous in many parts of the world, utilizing them as biosensing platforms can enable access to rapid and cost-effective diagnostics, particularly in resource-limited settings or remote areas. Smartphone-based biosensors can utilize its massive processing power by integration of AI and machine learning algorithms as they could enable the development of context-aware or personalized biosensing applications.

Smartphone based biosensors are generally based on the optical or electrochemical measurements [46]. The built-in cameras and displays in smartphones can be easily used for optical detection methods such as colorimetry or fluorometry [48]. Similarly, the electrochemical biosensors which are typically consist of a working electrode, reference electrode, and

Table 1: Biosensor for detection of microbial toxin in the food samples.

S. No.	Spoilage microbes	Food sample	Biosensor	Limit of detection	Advantages	Ref.
1	Aflatoxin B_1	Food	Competitive quenching electrochemiluminescence immunosensor	4.56 fg/ml	Sensitive, specific	[50]
2	Aflatoxin B_1	Food	Ratiometric dual-signal electrochemical aptasensor	0.12 pM	Rapid and sensitive	[51]
3	Aflatoxin	Saffron	Colorimetric competitive assay-based sensor	of 4 pg ml^{-1}	Simple, cost effective, specific	[52]
4	Microbial Toxins	Food	Nanomaterial-based electrochemical biosensors	-	Sensitive, rapid, reliable, cost-effective	[53]
5	Aflatoxin B_1	Peanut and other agricultural products	Sensitivity-programmable ratiometric electrochemical aptasensor	0.016 ng ml^{-1}	Excellent selectivity, reliability, reproducibility	[54]
6	Ochratoxin A	Food	Colorimetric biosensor based on enzyme-induced gold nanoparticle aggregation	5.0 nm	Applicable without pretreated samples, high specificity	[55]
7	Aflatoxin B_1	Spiked peanut	SERS aptasensor based on exonuclease-assisted recycling amplification	0.4 fg/ml	Highly sensitive	[56]
8	Aflatoxin B_1	Agricultural and food samples	Humanoid-shaped fiber optic Wave Flex biosensor	34.5 nM	High stability, selectivity, reproducibility, and reusability	[57]
9	Ochratoxin A	Food	Nanomaterial-based optical biosensors	-	Rapid and on-site	[58]
10	Ochratoxin A	Red wine samples	DNA walker-based dual-signal electrochemical ratiometric platform	0.31 fg/ml	Superior sensitivity	[59]
11	Ochratoxin A	Apple juice	Electrochemical sensor based on $MnCO_3$ nanostructures	2.0 x 10^{-12} ml^{-1}	Superior stability, repeatability, and reproducibility	[60]
12	Patulin	Fruits, vegetables, and their products	Aptamer-based lateral flow assay using streptavidin functionalized gold nanoparticles	0.19 ng/ml	Rapid, simple, on-site screening	[61]

Table 2: Biosensors for the detection of bacteria in the spoiled food samples.

S. No.	Spoilage microbes	Food sample	Biosensor	Limit of detection (in CFU/ml)	Advantages	Ref.
1	*Vibrio parahaemolyticus*	Shellfish, Oyster	Duplex electrochemical biosensor	1	High specificity, duplexing capability, portable, assess virulence	[62]
2	*Listeria monocytogenes*	Food	Optical immunosensor	3.2	Sensitive, greener approach	[63]
3	*Escherichia coli*	Seawater/Milk	Fast scan voltammetry-based electrochemical sensor	1	Single cell determination	[64]
4	*V. parahaemolyticus*	Cod samples	Fluorescence resonance energy transfer-based paper sensor	6.7×10^1	High sensitivity, portable, specific	[65]
5	*E. coli*	-	Electrochemical sensor	1	-	[64]
6	*V. parahaemolyticus*	Shrimp samples	Dual-mode colorimetric-electrochemical biosensor	30	High accuracy	[66]
7	*Salmonella*	Food	Electrochemiluminescence sensor	37	Detect in real sample	[67]
8	*Salmonella*	Food	Probe-free electrochemical nanosensor with gold nanorods	23	Rapid and sensitive	[68]
9	*Salmonella typhimurium* (St) and *V. parahaemolyticus* (Vp)	Food	Fluorescent aptasensor	30 (St) and 10 (Vp)	Superior specificity, anti-interference ability, and sensitivity	[69]
10	*V. parahaemolyticus*	Food	Dual mode aptasensor with colorimetric (CM) and electrochemical detection (EC)	30 (CM) and 5 (EC)	Dual mode detection, sensitive	[70]
11	*Staphylococcus aureus* (Sa) and *E. coli* (Ec)	Food	Biosensor based on bacteria-initiated *in situ* growth of electroactive polymers	4 (Sa) and 6 (Ec)	Sensitive	[71]
12	*V. parahaemolyticus*	-	DNA walker-mediated biosensor	1	High sensitivity and accurate	[72]
13	*S. typhimurium*	Milk	$Cu_3(PO_4)2$-mediated click chemistry and DNA zymes-based electrochemical biosensor	10	Sensitive, dual signal amplification	[73]
14	*V. parahaemolyticus*	Seafood	Microfluidic thread-based electrochemical aptasensor	5.74	High sensitivity	[74]
15	*S. aureus, Shigella flexneri, Pseudomonas aeruginosa, V. parahaemolyticus, Bacillus subtilis, E. coli* O157:H7, and *S. typhimurium*	Food	Low pH-based colorimetric assay and unfunctionalized gold nanoparticlesbased biosensor	1.6×10^7 to 6.6×10^6 #	Simple, visual, rapid	[75]
16	*P. aeruginosa*	Food	Aptamer-based biosensors	-	Rapid, accurate, specific, and ultrasensitive	[76]
17	*V. parahaemolyticus*	Food	Faraday cage-type aptasensor	1.7	-	[77]
18	*L. monocytogenes* and *S. aureus*	Food	Ultrasensitive peptide-based multiplexed electrochemical biosensor	9	Ultrasensitive	[78]
19	*L. monocytogenes*	Milk	Electrochemical DNA biosensor	82 fg/6 µl	-	[79]
20	*L. monocytogenes* (Lm) and *S. aureus* (Sa)	Food samples	Peptide-based multiplexed electrochemical biosensor	9 (Lm); 3 (Sa)	Rapid detection in 1 min, ultra-sensitive, rapid, simple and cost-effective simultaneous detection	[78]
21	*Salmonella enterica*	Milk	Electrochemical biosensors utilizing nanomaterials	0.3 pg/ml	Sensititve, specific	[80]
22	*V. parahaemolyticus*	Seafood	Graphene-based screen-printed electrochemical sensor	0.3 CFU per 25 g	Point-of-care device for on-site detection	[81]
23	*E. coli, P. aeruginosa*	Coconut water	Gold nanorods based sensor	10^3	Sensitive, selective, rapid	[82]
24	*E. coli*	-	T4 bacteriophage-immobilized multimode microfiber	10^3	Rapid, specific, sensitive	[83]
25	*L. monocytogenes*	Food	Electrochemical impedance spectroscopy as fluorescence-free biosensing technologies	1	-	[84]
26	*S. aureus*	Food	Paper-based biosensor	7, 40, and 100	Detectable by naked eyes, quantitative measurement, sensitive	[85]
27	*Salmonella*	Food	Sandwich electrochemical immunosensor	3.0×10^3	Sensitive, highly specific, acceptably accurate, reproducible	[86]

Note: # is varies with the different microorganisms, and * is variation in unit.

Table 3: Biosensors to detect gases and spoilage causing substances in the food samples.

S. No.	Spoilage compound	Food	Biosensor	Limit of detection	Advantages	Ref.
1	Ammonium and various gases	Pork	Printable colorimetric food sensor	> 300 ppb and 1 ppm	Rapid, colour change in 3 min	[87]
2	Hydrogen sulfide	Food sample	Colorimetric biosensors based on silver nanoparticles	> 20 mg/L	Sensitive	[88]
3	Glutathione detection	Food	Smartphone-assisted colorimetric and photothermal probe-based sensor	0.092 μm	Simple, rapid, low cost, portable, high sensitivity, and accuracy	[89]
4	Hydrogen sulfide by Psychro-trophic bacteria	Meat	Dual fluorometric and colorimetric sensor	0.181 μm	Sensitive, selective	[90]
5	Ammonia	Pork	Printable sensors based on a hydro-gel-containing pH indicator	300 ppb and 1 ppm	Rapid, reproducible	[87]
6	Hydrogen sulfide	Meat, broiler poultry	Colorimetric sensor	2 mg/m^3	Rapid, real-time, nondestructive detection	[91]
7	Hydrogen sulfide	Meat	Nano-bionic sensor	15.6 nm	Sensitive, selective	[92]
8	Ammonia	Food samples	Eco-friendly paper-based gas sensors	-	-	[93]
9	Ammonia	Protein-rich foods	Gas sensor based on flexible poly-aniline films	50 - 150 ppm	Sensitive	[94]
10	Ammonia	Food	gas sensor based on (001) TiO_2/ MXene heterostructure	156 ppt	Sensitive	[95]
11	Food allergens	Food	Screen-printed electrodes	-	Easy to use, portable, point of care detection, robust	[96, 97]
12	Biogenic amine dopamine, hista-mine, tryptamine	Meat	Naphthyl end-capped terthio-phene-based chemiresistive sensors	> 22 ppm	High sensitivity	[98]
13	Hydrogen sulfide	Chilled broiler meat	Genetically encoded fluorescent biosensors	2 mg/m^3	Specificity	[99]
14	Ammonia	Food	Polyaniline films-based sensor	-	Small size, low cost, flexibility, low power consumption and high sensitivity	[100]

counter electrode [49]. and can easily be connected to smartphones using the USB interface. Smartphone-based optical biosensors have been applied to detect various spoilage indicators, such as specific bacteria, enzymes, gases, and volatile organic compounds VOCs produced during food spoilage. To enhance the sensitivity of electrochemical biosensors, signal amplification strategies are employed.

Different types of biosensors for the detection of toxins, presence of bacteria in different food samples and for detecting the gases produced by spoilage of food are presented in table 1, table 2 and table 3 respectively.

This can include the use of nanomaterials like gold nanoparticles or graphene to improve the signal-to-noise ratio or enzymatic amplification techniques such as enzyme-linked immunosorbent assay-like reactions. Several such smartphone-based biosensors for monitoring of food quality have reached commercialization or are in advanced stages of development. For example, Bio Systems Inc. has developed a handheld device named "Food sniffer", and Nano scent Ltd. has made "Nano scent" that can detect the presence of volatile organic compounds VOCs emitted by food as it spoils. "eNose" by Aryballe Technologies and Olfaguard" by Olfaguard AB are other such example of odor-detection device that can be connected to a smartphone for detection of food spoilage. These technologies have facilitated the development of on-site and point-of-care sensing abilities.

Discussion

The advancements in the field of nanotechnology, AI, and biosensors have revolutionized the field of food quality control and safety. The capabilities of biosensors have witnessed a multi-fold improvement by the incorporation of machine learning and data analytics with more effective IoT enabled biosensors made from nanomaterials. Microfluidics based lab on a chip device combined with the smartphones offer real-time data monitoring and analysis. Advanced machine learning and AI based techniques make it possible to extract important information from this complicated sensor data, increasing the precision of spoiling detection. Training of pattern recognition and classification algorithms on data from multiple biosensors enable the identification of spoilage patterns, facilitating early intervention and preventing further deterioration. Moreover, the predictive modelling using biosensor data allow for the assessment of remaining shelf life, which offers useful information for inventory management and waste minimization.

These developments have important ramifications for various stakeholders in the food industry, such as food producers, distributors, and consumers. Spoilage detection can greatly help food producers by reducing the wastage and guaranteeing the delivery of high-quality goods, which will automatically enhance the consumer satisfaction. These innovations have tremendous potential to improve food quality control,

cut down on waste, and ensure the security of our food supply chain, eventually helping not only the consumers and farmers but also the environment. Nevertheless, there are still challenges to be addressed despite the impressive advancements in biosensor technology. Further research and development are needed to optimize sensor performance, integration with IoT and microfluidic technologies and improve the accuracy of predictive models. Additionally, practical aspects like cost, scalability, and ease of use also need to be considered when applying biosensors in real-world applications.

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None.

Conflict of Interest

None.

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