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Review

Applications of commercial biosensors in clinical, food, environmental, and biothreat/biowarfare analyses

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ABSTRACT

The lack of specific, low-cost, rapid, sensitive, and easy detection of biomolecules has resulted in the development of biosensor technology. Innovations in biosensor technology have enabled many biosensors to be commercialized and have enabled biomolecules to be detected onsite. Moreover, the emerging technologies of lab-on-a-chip microdevices and nanosensors offer opportunities for the development of new biosensors with much better performance. Biosensors were first introduced into the laboratory by Clark and Lyons. They developed the first glucose biosensor for laboratory conditions. Then in 1973, a glucose biosensor was commercialized by Yellow Springs Instruments. The commercial biosensors have small size and simple construction and they are ideal for point-of-care biosensing. In addition to glucose, a wide variety of metabolites such as lactate, cholesterol, and creatinine can be detected by using commercial biosensors. Like the glucose biosensors (tests) other commercial tests such as for pregnancy (hCG), *Escherichia coli* O157, influenza A and B viruses, *Helicobacter pylori*, human immunodeficiency virus, tuberculosis, and malaria have achieved success. Apart from their use in clinical analysis, commercial tests are also used in environmental (such as biochemical oxygen demand, nitrate, pesticide), food (such as glutamate, glutamine, sucrose, lactose, alcohol, ascorbic acid), and biothreat/biowarfare (*Bacillus anthracis*, *Salmonella*, *Botulinum* toxin) analysis. In this review, commercial biosensors in clinical, environmental, food, and biowarfare analysis are summarized and the commercial biosensors are compared in terms of their important characteristics. This is the first review in which all the commercially available tests are compiled together.

A biosensor is an analytical device that integrates a biologically derived recognition of molecules such as enzymes, antibodies, phages, aptamers, or single-stranded DNA with a suitable physicochemical transducer. Electrochemical, optical, thermometric, piezoelectric, and magnetic transducers are the common types. Apart from these biosensors, there are immunochromatographic devices, which do not use any of the transducers mentioned above. These devices are based on lateral flow strips and they are ultrasensitive tests and enable for on-site visual detection of target molecules. In this field, the most successful lateral flow strip products are the home pregnancy strip and glucose testing strip, which have been widely commercialized. Biosensors generally produce an electronic or optical signal proportional to the specific interaction between the target and the recognition molecule immobilized on the biosensor. They also transform biological interactions into electronic signals that can be properly measured and recorded. A wide range of subjects from small protein molecules to large pathogens can be detected by biosensors [1]. In biosensor types, electrochemical biosensors are more suitable for onsite analysis and also they can easily be miniaturized for handheld devices. A commercial biosensor, except for immunochromatographic devices, generally consists of a detector and a sample application and delivery system. All of them vary depending on the manufacturer and the related application [2].

Glucose-testing biosensors and pregnancy tests are commonly used biosensors in medicine, which has huge market potential. Food, agriculture, the military, veterinary services, and the environment are potential markets for commercial biosensors [3]. Areas of usage of commercial biosensors are shown in Fig. 1. The global market for biosensors is estimated to reach US$12 billion by the year 2015. Growth in population and increases in the number of people affected with various diseases such as diabetes, obesity, and cancer are driving the need for medical care [4]. The market share of biosensors would be probably larger if the

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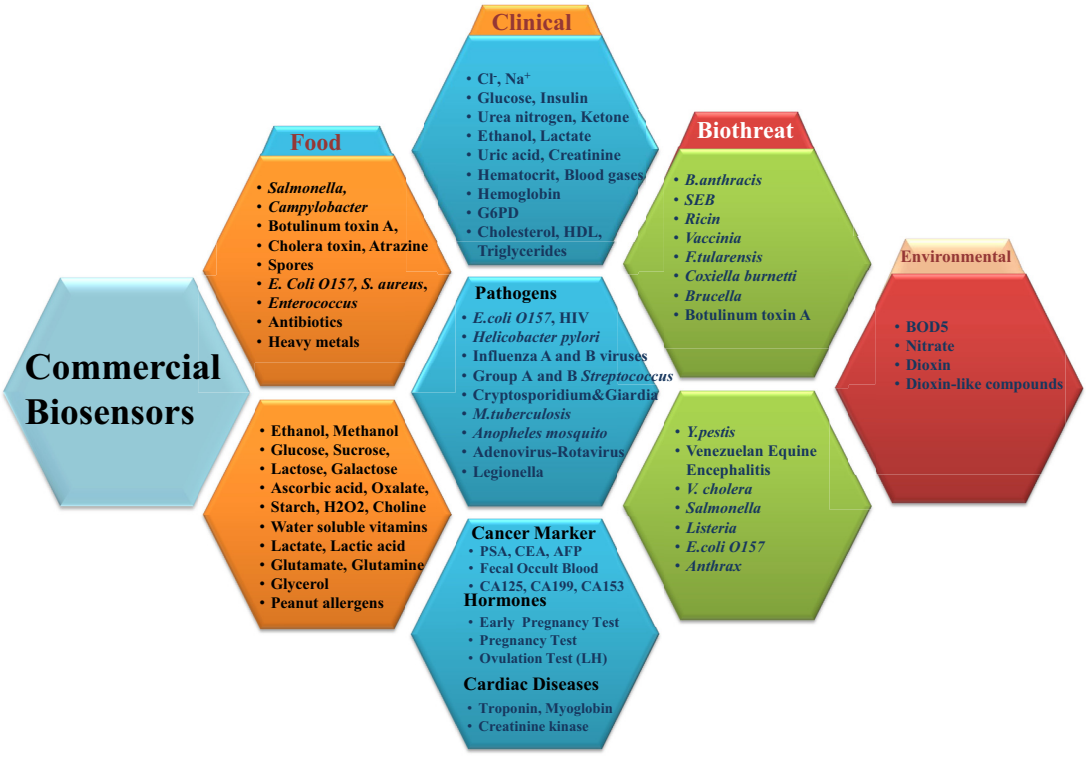

Fig.1. Commercially available biosensors on the world market.

considerable academic research on biosensors could be performed. And also the gap between developed biosensors and their practical use would be closed if the academically developed biosensors could be applied on real samples. In this review the widely used commercial biosensors are summarized and their properties are compared. The summarized commercial biosensors in this review are available in markets, drug stores, and Web sites. This study is distinguished from others by being the first review that summarizes all the biosensors on the global market and also presents the improvement of the biosensor market.

Commercial biosensors in clinical analysis

Diagnosis and monitoring of various diseases require too much effort for routine tests of blood samples and other associated tests. And these routine techniques require typical analytical techniques, specialized personnel, time, and high sample volumes. However, biosensors have many advantages such as low cost, high sensitivity, fast response, and easy operation for analyte detection. Also biosensors do not require expensive instrumentation and specialized personnel.

Commercial glucose biosensors

Blood glucose measurement has a vital role for management of diabetes. It is a metabolic disturbance that occurs when the pancreas does not produce enough insulin or when the body cannot effectively use insulin. This leads to high concentrations of glucose in the blood (hyperglycemia). Three hundred forty-seven million people worldwide have diabetes [5]. Because diabetic patients need to routinely track their blood glucose concentrations, the self-monitoring of blood glucose is important for the prognosis of diabetes and an effective method of measuring blood sugar in clinics, at home, and in the workplace is needed.

A portable glucose testing meter (commercialized biosensor) should be functional, compact, safe, and low cost. They are based on disposable, screen-printed enzyme electrode test strips. These plastic or paper strips have electrochemical cells that contain an enzyme and a redox mediator [6]. Initially, a test strip is inserted into the meter, and then a small drop of blood, which is obtained from the fingertip with a lancing device, is applied to the test strip. Finally, the result is displayed.

Enzymatic amperometric glucose biosensors are the most common commercially available devices and have been widely studied over the past decades. In commercial glucose tests two enzymes are mostly used: glucose oxidase (GOx) and glucose dehydrogenase. Glucose oxidase is an oxygen-dependent enzyme that has been used for a long time in the construction of glucose biosensors. Since GOx uses oxygen as an electron acceptor, there is a competition between the artificial mediator and oxygen mediation. When the oxygen level is high in blood, the glucose level in blood may appear lower than the true value. Because of this, some other enzymes such as pyrroloquinoline–quinone-dependent glucose dehydrogenase have been used for developing glucose tests. Using with this system the level of oxygen does not affect the reaction, because this enzyme does not use oxygen as an electron acceptor.

In 1973, Yellow Springs Instruments (Yellow Springs, OH, USA) developed a benchtop glucose analyzer for the first time. It is based on reactions catalyzed by oxidase enzyme and subsequent detection of H_2O_2 on platinum electrodes [6,7].

The commercialized second-generation glucose biosensors are in a single-use testing format. MediSense (Waltham, MA, USA) was the first company to put one on the market. These biosensors were pen-sized and used for testing blood glucose in home. The mediation was performed with ferrocyanide and in this biosensor glucose dehydrogenase was used as a biorecognition element. In March 1996, Abbott Laboratories (Abbott Park, IL, USA) purchased MediSense. Consequently, other second-generation amperometric

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Table 1
Commercially available clinical biosensors and their characteristics.

Company	Model	Analyte	Measuring range (mM)	Stability
Yellow Springs Instruments	23A	Glucose	1–45	300
	13L	Lactate	0–15	
	27	Ethanol	0–60	
Zentrum für Wissenschaftlichen Geratebau, Berlin, Germany	Glucometer	Glucose	0.5–50	>1000 samples;
		Uric acid	0.1–1.2	10 days
Fuji Electric, Tokyo, Japan	Gluco 20	Glucose α-amylase	0–27	>500 samples
Pulsatum Health Care Ltd, India	Glucometer	Glucose	0–600 mg/dl	6 months
Abbott, USA	FreeStyle Life	Glucose	20–500 mg/dl	—
	FreeStyle Freedom	Glucose	20–500 mg/dl	—
	FreeStyle InsuLinx	Glucose, insulin	20–500 mg/dl, —	—, —
	Precision Xtra Overview	Glucose, ketone	—, —	—, —
EKF Industrie-Elektronik GmbH	Biosens 040	Glucose	—	—
Daiichi, Kyoto, Japan	Autostat GA-1120	Glucose	1–40	—
Roche, Basel, Switzerland	LA 640	Lactate	0.5–12	40 days
	Accu-chek Aviva Plus	Glucose	—	—
	Accu-chek Nano Smart	Glucose	—	—
	Accutrend Plus System	Glucose, cholesterol	20–600 mg/dl, 150–300 mg/dl	—, —
Eppendorf, Germany	ADM 300	Glucose	1–100	>2000 samples; 10 days
	ECA 20 (ESAT 6660)	Glucose, lactate	0.6–60, 1–30	14 days
	ACC	Uric acid, lactate	0.1–1.2, 1.2–18.7	10 days
Accusport lactate analyzer (ACC)	—	Total cholesterol, alcohol	—, 0.1%	
Lifestream cholesterol monitor	i-STAT	Glucose		
Alcosan saliva alcohol dipstick	PCA	Urea nitrogen, Cl^-, K^-, Na^+, hematocrit blood gases		
	HHxx series	Water, urine, blood	0–25000 ± 6.1 PA	
TFS biosensor fluorometers	—	HIV whole blood	—	
Ultra compact analyzer (Akers Bioscience, Inc.)	BIAcore 2000	Biomolecular interactions	10^{-3}–10^{-10}	
BIAcore AB SPR instrumentation	—	Glucose		
DEX blood glucose meter	Bioscanner 2000	Glucose, cholesterol, HDL, blood ketone, triglycerides		—
Bioscanner 2000 home blood testing kit and glucose monitor	—	Hemoglobin		
HemoCue B hemoglobin analyzer	Glucometer Elite XL	Glucose	20–600 mg/dl	—
Elite glucometer	Lactate Pro LT-1710	Lactate	0.8–23	—
KDK lactate analyzer				
HemoCue		Glucose	—	—
GEM		Blood gas	—	—
Lifescan, UK	One Touch Verio IQ	Glucose	—	—
	One Touch Verio Sync	Glucose	—	—
	One Touch Ultra Mini	Glucose	—	—
	One Touch Ping	Glucose	—	—
	One Touch Ultra 2	Glucose	—	—
Bayer, Canada	Contour meter	Glucose	—	—
	Contour Next meter	Glucose	—	—
	Contour Next USB meter	Glucose	—	—
	Contour Next Link meter	Glucose	—	—
	Contour Next EZ meter	Glucose	—	—
	Contour USB meter	Glucose	—	—
	Contour Link meter	Glucose	—	—
	DIDGET meter	Glucose	—	—
	BREEZE 2 meter	Glucose	—	—
	Microlet 2 lancing device	Glucose	—	—
Nipro Diagnostics, USA	TRUE METRİX	Glucose	—	—
	TRUE2go	Glucose	—	—
	TRUEresult	Glucose	—	—
	TRUEtrack	Glucose	—	—
	TRUEbalance	Glucose	—	—
	TRUEread	Glucose	—	—

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Table 1 (*continued*)

Company	Model	Analyte	Measuring range (mM)	Stability
Prodigy Diabetes Care, Charlotte, NC, USA	Prodigy AutoCode	Glucose	20–600 mg/dl	–
	Prodigy Pocket	Glucose	20–600 mg/dl	–
	Prodigy Voice	Glucose	20–600 mg/dl	–
Nova Diabetes, USA	Nova Max Plus	Glucose, ketone	–	–
	Nova Max Link	Glucose	–	–
Gediabetes, Taiwan	GE 100	Glucose	20–600 mg/dl	–
Aga Matrix, USA	Wavesense Presto	Glucose	50–400 mg/dl	–
EPS Bio Technology Corp, Taiwan	MDT2	Glucose	20–630 mg/dl	–
	EME	Glucose	20–630 mg/dl	–
	EMM	Glucose	20–630 mg/dl	–
	EMV2	Glucose	20–630 mg/dl	–
	MasterDriver	Glucose	20–630 mg/dl	–
	R13 N	Glucose	20–630 mg/dl	–
American Screening Corp., USA	Q. STEPS G/C ADMS	Glucose, cholesterol	100–400 mg/dl	–
Omnis Health, USA	Embrace Meter	Glucose	–	–
	Embrace Evo	Glucose	–	–
	Embrace Pro	Glucose	–	–
Simple Diagnostics, USA	Clever Choice Voice HD	Glucose	20–600 mg/dl	–
	Clever Choice HD	Glucose	20–600 mg/dl	–
	Clever Choice Mini	Glucose	20–600 mg/dl	–
	Clever Choice Pro	Glucose	20–600 mg/dl	–
Medline, USA	EvenCore G3	Glucose	20–600 mg/dl	96 weeks
	EvenCore G2	Glucose	20–600 mg/dl	96 weeks
Bionime, Taiwan	GM 700	Glucose	100–600 mg/dl	–
	GM 720		100–600 mg/dl	–
	GM 700S		100–600 mg/dl	–
	GM 260		100–600 mg/dl	–
	GM 550		100–600 mg/dl	–
	GM 100		100–600 mg/dl	–
	GM 300		100–600 mg/dl	–
Advocate, USA	Advocate Redi-Code + BMB-E 001A	Glucose	–	–
	Advocate Redi-Code + BMB-E 001S	Glucose	–	–
MHC Medical Products, USA	Easy Touch	Glucose	20–600 mg/dl	–
ACON, China	On Call Vivid	Glucose	–	–
	On Call Chosen	Glucose	–	–
	On Call Platinum	Glucose	–	–
	On Call Resolve	Glucose	–	–
	On Call Advanced-Dependable & Advanced On Call E2 II	Glucose	–	–
	On Call Redi-Reliable	Glucose	–	–
	On Call Plus	Glucose	–	–
	On Call E2	Glucose	–	–
Germaine Laboratories, Inc., USA	AimStrip hemoglobin meter	Hemoglobin	–	–
	AimStrip Hemoglobin Starter Kit 200	Hemoglobin	–	–
	AimStrip hemoglobin test combo	Hemoglobin	–	–
Syntron Bioresearch, Inc., USA	Glucose monitoring system	Glucose	–	–
	Total cholesterol test	Cholesterol	–	–
ApexBio, Taiwan	Eclice Alc	Hemoglobin	4–14%	–
	GlucoSure AutoCode	Glucose	20–600 mg/dl	–
	GlucoSure Voice	Glucose	20–600 mg/dl	–
	HemoSmart	Hemoglobin	4–20 g/dl	–
	MultiSure	Glucose, uric acid	30–550 mg/dl, 3–20 mg/dl	–, –
	GlucoSure Star	Glucose	20–600 mg/dl	
	GlucoSure Plus	Glucose	30–50 mg/dl	–
	UASure	Uric acid	3–20 mg/dl	–
	The Edge	Lactate	6–200 mg/dl	–
Arkay, Japan	Glucocard 01	Glucose	10–600 mg/dl	–
	Glucocard 01 Mini	Glucose	10–600 mg/dl	–
	Glucocard 01 Mini Plus	Glucose	10–600 mg/dl	–
	Glucometer X-meter GT-1910	Glucose	10–600 mg/dl	–
	Glucocard X-Mini	Glucose	10–600 mg/dl	
	Glucocard X-Mini Plus	Glucose	10–600 mg/dl	–
	Glucocard $\sum$	Glucose	10–600 mg/dl	–
	Glucocard $\sum$-mini	Glucose	10–600 mg/dl	–

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Table 1 (*continued*)

Company	Model	Analyte	Measuring range (mM)	Stability
EKF Diagnostics, USA	Lactate Pro-2 LT-1730	Lactate	0.5–25 mmol/L	–
	Lactate Scout	Lactate	0.5–25 mmol/L	–
	STAT-Site-M$^{B\text{-}HB}$	Ketone	0.1–2 mM	–
	STAT-Site-M^{Hgb}	Hemoglobin	4–21 g/dl	–
Nova Biomedical, USA	Stat Strip GLU	Glucose	–	–
	Stat Strip GLU/KET	Glucose, ketone	–, –	–, –
	Stat Strip LAC	Lactate	–	–
	Stat Strip CREAT	Creatinine	–	–
	Stat Strip Glucose Xpress	Glucose	20–600 mg/dl	–
	Stat Strip Xpress GLU/KET	Glucose, ketone	–, –	–, –
	Stat Strip Xpress LAC			
	Stat Strip Xpress CREAT	Lactate	–	–
	Nova MAX Plus	Creatinine	–	–
	Lactate Plus	Glucose, ketone	–, –	–, –
	Nova Max Link®	Lactate	–	–
		Glucose	–	–
Pts Diagnostics, China	CardioChek	Cholesterol	–	–
	CardioChek PA	Cholesterol	–	–
	CardioChek P	Cholesterol	–	–

Data from Refs. [9].

Table 2
The technical characters of glucose testing meters.

Features	Brand				
	FreeStyle	Bayer	Lifescan	Yicheng	Acon
Sample volume (μl)	0.3	0.6	1	0.5	1
Test time (s)	5	5	5	5	10
Precision (%)	CV ⩽ 3	CV ⩽ 5.3	CV ⩽ 4.4	CV ⩽ 7.5	CV ⩽ 5.5
Hematocrit	20–70	15–65	20–70	35–55	35–55
Correlation efficient (γ)	0.98	0.98	0.98	0.95	0.97
Enzymes used	GDH	GDH	GOx	GOx	GOx
Mediators	Os complex	Ferricyanide	Ferricyanide	Ferricyanide	Ferricyanide
Enzyme loading	Screen-printing	Screen-printing	Screen-printing	Screen-printing	Dispensing
Strip needs coding	Yes	No	Yes	Yes	Yes
CE/FDA approval	Yes	Yes	Yes	No	CE only

Data from Ref. [8]. GDH, glucose dehydrogenase; GOx, glucose oxidase.

biosensors have come on the market. Nowadays, apart from the ferrocyanide mediator, benzoquinone, hexaammineruthenium(III) chloride, and osmium(II) polypyridine are mostly used for the construction of commercial glucose tests [8].

Third-generation glucose biosensors are based on direct electron transfer between enzyme and the electrode. The electrode can perform direct electron transfers by using organic conducting materials. Therefore, this design facilitates repeated measurements and these biosensors are implantable, needle-type devices for continuous in vivo monitoring of blood glucose [6,9].

Nowadays two types of continuous glucose-monitoring systems are used for continuous subcutaneous glucose monitoring and continuous intravenous blood glucose monitoring. Most of the continuous intravenous glucose monitoring systems have disadvantages such as surface contamination of the electrode by proteins and coagulation factors and the risk of thromboembolism, and thus they do not measure blood glucose directly. Therefore, subcutaneously implantable needle-type electrodes have been developed for measuring glucose concentrations in interstitial fluid.

Noninvasive glucose analysis is used for glucose monitoring. Optical or transdermal devices are the most common noninvasive glucose-sensing methods. The glucoWatch Biographer, produced by Cygnus, Inc. (Redwood City, CA, USA), was the first transdermal glucose sensor that was approved by the U.S. Food and Drug Administration. The principle of this watch-like device was transdermal extraction of interstitial fluid by reverse iontophoresis. Owing to a long warm-up time, false alarms, inaccuracy, skin irritation, and sweating, it was not presented on the market. Also, it was withdrawn in 2008 [6].

The commercially available biosensors and their characteristics are shown in Table 1 [9]. The technical characters of glucose testing meters are compared in Table 2 [8].

Commercial human chorionic gonadotrophin (hCG) biosensors

Human chorionic gonadotrophin is a glycoprotein hormone secreted by the trophoblast cells of the placenta during pregnancy [10]. The most successful home-use protein-detection biosensor is the pregnancy test. It detects hCG in urine and its principle is the lateral-flow immunochromatographic technique. The test is fabricated with a nitrocellulose membrane with a sample application pad and an absorbent pad at the two ends. An integration pad, which embeds monoclonal anti-hCG antibody conjugated with dye label, is sandwiched between the sample application pad and the nitrocellulose membrane. The absorbent pad end of the nitrocellulose membrane includes one test line and one control line with antibodies against hCG and the monoclonal antibody immobilized on it. When a urine sample is applied to the sample application pad, it is transported toward the absorbent pad by

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Table 3
Commercial biosensors for hCG.

Company	Model	Sensitivity
Coretests, China	HCG pregnancy test (midstream)	25 mIU/ml
	HCG pregnancy test (cassette)	25 mIU/ml
	HCG pregnancy test (strip)	25 mIU/ml
Egens Diagnostics Corp., USA	Pregnancy test kit	–
United Surgical & Diagnostics, India	Pregnancy testing strips and cards	–
Alere, USA	Alere hCG cassette (20 mIU/ml)	20 mIU/ml
	Alere hCG Combo cassette (20/10 mIU/ml)	20 mIU/ml in urine, 10 mIU/ml in serum
	Alere hCG dipstick	25 mIU/ml
	Alere hCG Combo cassette (25 mIU/ml)	25 mIU/ml
	Alere hCG cassette (25 mIU/ml)	25 mIU/ml
	Alere hCG Easy Pregnancy	25mIU/ml
Clearblue, USA	Clearblue Digital	–
	Clearblue Plus	–
AccuBio Tech Co. Ltd, USA	Accu-Tell Rapid hCG pregnancy urine test	25 mIU/ml
Medic8, Scotland	Accu-Clear pregnancy test	–
Bluecross, China	One Step pregnancy test (hCG)	–
Clinical Guard, USA	25 One Step hCG pregnancy test strip	–
SERATEC Gesellschaft für Biotechnologie GmbH, Germany	SERATEC Combo pregnancy test	20 mIU/ml
Easy Home Medical, USA	Pregnancy test	–
Church & Dwight Co., Inc., Canada	FIRST RESPONSE early result pregnancy test	–
	FIRST RESPONSE rapid result pregnancy test	–
	FIRST RESPONSE Gold digital pregnancy test	–
Germaine Laboratories, Inc., USA	AccuHome pregnancy	25 mIU/ml
	AimStep Combo pregnancy	20 mIU/ml
	AimStep pregnancy	20 mIU/ml
	AimStrip Combo pregnancy	20 mIU/ml
	AimStrip pregnancy	20 mIU/ml
Stanbio Laboratory, USA	QUPID pregnancy test	20 mIU/ml
Pfizer Consumer Healthcare, USA	e.p.t. pregnancy test	–
	e.p.t. digital pregnancy test	–
ACON Laboratories, China	ACON One Step pregnancy test	10–25 mIU/ml
Syntron Bioresearch, Inc., USA	Pregnancy test	25 mIU/ml
BR Pharmaceuticals, USA	Reveal pregnancy test	25 mIU/ml
Quidel Corp., USA	Sofia hCG FIA	–
	QuickVue + hCG Combo test	20 mIU/ml
	QuickVue hCG Combo test	25 mIU/ml
	QuickVue hCG urine test	25 mIU/ml

Data from Refs. [34–49,27,50,51].

capillary action. In the presence of hCG, the dye label is captured in both the test and the control lines [7]. The test is sensitive down to nanomolar (10^{-9}) or lower concentrations of hCG. The commercial biosensors for hCG are summarized in Table 3.

Commercial biosensor for Escherichia coli O157

E. coli O157 is one of the most representative serotypes of enterohemorrhagic *E. coli*. It can produce Shiga-like toxin and causes life-threatening gastrointestinal infections, such as bloody diarrhea, hemorrhagic colitis, renal failure, and meningitis [52]. Commercial tests have played important roles in pathogenic bacteria detection. Commonly, they are used for detection of *E. coli* O157:H7 in stool specimens or culture. The commercial biosensors for *E. coli* O157 are summarized in Table 4 [52]. The detection of *E. coli* O157 with a strip biosensor is a one-step, easy procedure and provides more accurate results in a short time [54].

Commercial biosensor for influenza A and B viruses

Influenza viruses are members of the family Orthomyxoviridae, of the group of ssRNA viruses with negative polarity. This family consists of three genera: *Influenza A*, *Influenza B*, and *Influenza C*. Species-specific nucleoprotein antigens, the number of gene segments, host specificity, and clinical manifestations are different for each genus [55].

There are a number of methods for influenza virus detection in respiratory specimens. Laboratories previously used viral culture to detect influenza virus and monitored the improvements in virus culture, and these techniques took a long time (48–72 h). The direct fluorescent antibody method takes 2–3 h for detection of virus, but it needs considerable experience. Molecular methods such as reverse transcription polymerase chain reaction-based tests are the most accurate methods to detect influenza virus, but they are expensive and require expensive equipment and trained technologists. The commercial influenza A and B virus test offers rapid diagnosis of acute influenza type A and type B viral infections. These tests are based on rapid chromatographic (lateral flow) immunoassays for the direct, qualitative detection of these viruses in respiratory specimens. A color change appears based on influenza A and influenza B being positive or negative [56]. The commercial tests for influenza A and B viruses are summarized in Table 5. These commercial tests offer the possibility of identifying an infected patient early.

Commercial biosensor for Helicobacter pylori

H. pylori is a gram-negative rod bacterial pathogen that is found in the mucous layer of the antral and fungal gastric epithelium and sometimes in ectopic gastric tissue in the duodenum or esophagus. It is highly motile owing to its flagella, so it can move within the mucous layer of the stomach. Medications for this disease can eradicate this organism [63]. The diagnostic tests for detection of *H. pylori* include an invasive method, which requires gastric endoscopy and tissue biopsy, and a noninvasive method, which requires only specimen types. The test is easy to perform in a one-step procedure using two hanging drops of whole blood, serum, and plasma [64]. The commercial biosensors for *H. pylori* are summarized in Table 6.

Table 4
Commercialized biosensor for *E. coli* O157.

Company	Model
Coris BioConcept, Belgium	O157 Coli-Strip
	O157 Coli Uni-Strip
Meridian Bioscience, USA	ImmunoCard STAT! *E. coli* O157 Plus

Data from Refs. [53,54].

Table 5
The commercial biosensor for influenza A and B virus detection.

Company	Model	Sensitivity
Quidel, USA	QuickVue Influenza A + B test	A, 94%, B, 70%, nasal swab; A, 83%, B, 62%, nasopharyngeal swab; A, 77%, B, 82%, nasal aspirate/nasal wash
	Sofia Influenza A + B	A, 90%, B, 89%, nasal swab; A, 97%, B, 90%, nasopharyngeal swab; A, 99%, B, 88%, nasal aspirate/nasal wash
	Influenza test	Nasal swab, 73%; nasal wash/nasal aspirate, 81%
Alere, USA	Alere BinaxNOW Influenza A & B card	Flu A, 70–89%; flu B, 50–69%
	Alere Influenza A & B test	Flu A, 93.8%; flu B, 77.4%
Directigen EZ Flu A + B, USA	BD EZ Flu A + B test	—
SAS FluAlert A&B, USA	SA Scientific SAS FLUAlert A & B	—
Coris BioConcept, Belgium	Influ-A & B Respi-Strip Influ-A & B Uni-Strip	82.5 to 99.8%
Thermo, USA	Xpect Flu A & B	—
OraSure Technologies, Inc., USA	OraSure QuickFlu Rapid Flu A + B test	—

Data from Refs. [56–62].

Table 6
The commercial biosensors for *Helicobacter pylori* detection.

Company	Model	Sensitivity
Quidel, USA	QuickVue *H. pylori* test	Biopsy, 90%
Beckman Coulter, USA	Icon HP	95.9%
Coris BioConcept, Belgium	Pylori-Strip	98.2%
Meridian Bioscience, USA	ImmunoCard STAT! HpSA	90.6%
Medcare Biotech Co. Ltd, China	*H. pylori* test	—
Germaine Laboratories, Inc., USA	AimStep *H. pylori*	—

Data from Refs. [63–69].

Table 7
Commercial HIV biosensors.

Company	Model	Format
Runbio Biotech Co. Ltd, China	HIV 1 + 2 test strip	Strip
Hangzhou Clongene Biotech Co. Ltd, China	HIV test kit	Cassette
Ybio, China	RAPITEST HIV 1/2	Cassette
Alere, USA	Alere Determine HIV 1/2 Ag/Ab Combo	Strip
Medcare Biotech Co. Ltd, China	HIV saliva test (HIV T 01)	Strip
Ajosha Bio Teknik Pvt. Ltd, India	HIV test strip	Cassette
Nantong Egens Biotechnology Co. Ltd	One-Step Anti-HIV (1 + 2) antigen test (strip)	Strip/cassette
OraSure Technologies, Inc., USA	OraQuick In-Home HIV test	Cassette
	OraQuick ADVANCE Rapid HIV-1/2 antibody test	Cassette
Aittone Laboratories, Inc., China	Strip HIV 1/2 test	Cassette
ALUXBIO Co. Ltd, China	Oral Fluid HIV Rapid test	Cassette/ strip
Standard Diagnostics, Inc., Korea	SD Bioline HIV-1/2 3.0	Cassette
JAL Innovation, Taiwan	iCARE HIV 1 & 2 Rapid Screen test	Cassette

Data from Refs. [72–83].

Table 8
Commercial biosensor for tuberculosis.

Company	Model	Specificity
Alere, USA	Alere Determine TB LAM Ag	>98%
Standard Diagnostics, Inc., Korea	SD Bioline TB Ag MPT64	100%
Coretests, China	TB tuberculosis test (serum/plasma)	94.3%
United Surgical & Diagnostics, India	TB card test	—

Data from Refs. [84–86,36].

Table 9
Commercial biosensors for malaria.

Company	Model	Sensitivity for *Pf* malaria
Alere, USA	Clearview Malaria *Pf* test	96.00%
Clongene HEO or OEM, China	HEO malaria *Pv*/*Pf*	—
Bonaide, China	Malaria test strip	—
Fyodor Biotechnologies, USA	Urine malaria test	—
Egens Diagnostics, China	Malaria test kit	—
Access Bio, Inc., Korea	CareStart Malaria HRP2/pLDH (*Pf*/PAN) Combo	—
	CareStart Malaria HRP2/pLDH (*Pf*/VOM) Combo	—
	CareStart Malaria HRP2/pLDH (*Pf*/*Pv*) Combo	—
	CareStart malaria screen	—
	CareStart malaria pLDH (PAN)	—
	CareStart Malaria pLDH (*Pf*/PAN)	—
	CareStart Malaria HRP2 (*Pf*)	—
	CareStart Malaria pLDH (*Pf*)	—
	CareStart Malaria HRP2/pLDH (*Pf*)	—
Coretests, China	Malaria *Pf* and *Pv* antibody test (serum/plasma)	—
	Malaria *Pf* and *Pv* antigen test (serum/plasma)	—
	Malaria *Pf* and *Pv* Pan test (serum/plasma)	—

Data from Refs. [89–96].

Commercial biosensor for human immunodeficiency virus (HIV)

Acquired immunodeficiency syndrome is a disease of the human immune system caused by HIV. It attacks the immune system and destroys $CD4^+$ T lymphocytes of the immune system [70]. It is one of the most serious global health problems. Conventional diagnostic methods for HIV infection are blood tests such as enzyme immunoassay, enzyme-linked immunosorbent assay, and Western blot [71]. There are test kits that do not require sending

Table 10
Other commercial biosensors in clinical analysis.

Company	Model	Analyte
Access Bio, Inc., Korea	CareStart G6PD biosensor	G6PD
Run Bio Tech Co. Ltd, China	Rapid prostate-specific antigen diagnostic test	PSA
	Hepatitis C virus test strip	HCV
	Syphilis diagnostic test strip	*Treponema pallidum*
	Methamphetamine diagnostic test cassette	Methamphetamine
	Rapid fecal occult blood diagnostic test strip	Fecal occult blood
	Rapid gonorrhea diagnostic test strip	*Neisseria gonorrhoeae*
	Rapid α-fetoprotein diagnostic test	α-Fetoprotein
	Rapid amphetamine diagnostic screen test	Amphetamine
	Carcinoma embryonic antigen test	CEA
	Hepatitis B virus diagnostic test	HBV
Coris BioConcept, Belgium	Adeno-Strip	Adenovirus
	Adeno Uni-Strip	Adenovirus
	Legionella V-TesT	*Legionella*
	Rota-Strip	Rotavirus
	Rota Uni-Strip	Rotavirus
	Combi-Strip	Adenovirus–rotavirus
	Combi K-SeT	Adenovirus–rotavirus
	Combi K-SeT, with collection set	Adenovirus–rotavirus
	RSV Respi-Strip	Respiratory syncytial virus
	RSV K-SeT	Respiratory syncytial virus
	RSV K-SeT, with collection set	Respiratory syncytial virus

Data from Refs. [97–99].

Table 11
Commercial biosensors for the food industry.

Company	Biosensor	Country
Oriental Electric	Fish deterioration tracking	China
Massachusetts Institute of Technology	Detection of *E. coli* O157:H7 in lettuce (Canary)	USA
Michigan State University's electrochemical biosensor	Detection of *E. coli* O157:H7 and *Salmonella* in meat products in the USA	USA
Georgia Research Tech Institute	Detection of *Salmonella* and *Campylobacter* in the pork industry	USA
Naval Research Laboratory	Detection of *Staphylococcal enterotoxin B* and *Botulinum toxin A* in tomatoes, sweet corn, beans, and mushrooms	USA
Universitat Autonoma de Barcelona in collaboration with CSIC	Detection of atrazine traces	Spain
Molecular Circuitry, Inc.	*E. coli* O157, *Salmonella*, *Listeria*, and *Campylobacter*	USA
Research International	Proteins, toxins, virus, bacteria, spores, and fungi (simultaneous analysis)	USA
Universal Sensors	Ethanol, methanol, glucose, sucrose, lactose, L-AAs, glutamine, ascorbic acid, and oxalate	USA
Texas Instruments, Inc.	Peanut allergens, antibiotics	USA
Yellow Springs Instruments	Glucose, sucrose, lactose, L-lactate, galactose, L-glutamate, ethanol, H_2O_2, starch, glutamine, choline	USA
Affinity Sensors	*Staphylococcus aureus* and cholera toxin	UK
Ambri Ltd	Pathogens such as *Salmonella* and *Enterococcus*	USA
Biacore AB	Water-soluble vitamins, chemical veterinary residues, and mycotoxins	Sweden
BioFuture Srl	Glucose, fructose, malic acid, and lactic acid (fermentation)	Italy
Biomerieux	Microorganisms	France
Biosensor Systems Design	Microorganisms and toxic substances	USA
Biosensores S.L.	Toxic substances	Spain
Chemel AB	Glucose, saccharose, ethanol, methanol, and lactose	Sweden
IVA Co. Ltd	Heavy metals	Russia
Motorola	Microorganisms and genetically modified organisms	Japan
Iventus Bio Tec	Ascorbic acid	Germany
Analox Instruments	Ethanol, methanol, glucose, lactate, glycerol	UK, USA
Gwent Sensors	Glucose	UK

Data from Refs. [100,101].

samples to a laboratory for analysis. The kits provide quick results and self use. The test checks for antibodies to HIV in an oral fluid sample. One line in the strip will appear if the test is negative. Two lines indicate that HIV antibodies are detected and the test is positive. The commercial HIV biosensors are summarized in Table 7.

Commercial biosensor for tuberculosis

Tuberculosis (TB) is caused by *Mycobacterium tuberculosis*, which frequently affects the lungs. TB is spread from one person to another through the air when a person with active TB disease coughs or sneezes [84]. Commercial tuberculosis tests are based on one-step chromatographic immunoassay, which specifically detects the antibodies to *M. tuberculosis* in human serum or plasma. The test is sensitive and specific. The commercial biosensors for tuberculosis are summarized in Table 8.

Commercial biosensor for malaria

Malaria is an infectious disease widely spread in tropical and subtropical regions [87]. The bite of a female *Anopheles* mosquito

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Table 12
Selected commercial biosensors in food analysis.

Instrument	Enzymatic pathway	Analyte	Applied matrix	General comments
YSI 2700 Select food analyzer	Glucose oxidase Invertase/mutarotase/ glucose oxidase Galactose oxidase L-Lactate oxidase L-Glutamate oxidase Choline oxidase Glutaminase/L-Glutamate oxidase Alcohol oxidase Amyloglucosidase/ glucose oxidase	Glucose (dextrose) Sucrose Lactose L-Lactate L-Glutamate Choline L-Glutamine Ethanol Starch	Molasses, potatoes, milk Molasses, potatoes, milk Cheese, whey Lunch meat Chicken broth, spice mix, tomatoes Infant formula, pet food Cell culture Beer, wine Starch in foods	Automatically up to 24 samples 10- to 25-µl sample size Immobilization on polymeric membranes Typical membrane working life 5–21 days H_2O_2 anode oxidation Response time 1 min Precision CV (n −10) ~2%
ABD 3000 biosensor assay system	Lysine oxidase Alcohol oxidase L-Amino acid oxidase Ascorbate oxidase Glucose oxidase L-Glutamate L-Lactate oxidase Galactose oxidase Oxalate oxidase Invertase/mutarotase/ glucose oxidase	L-Lysine alcohol L-Amino acids Ascorbate Glucose Lactate Lactose/galactose Oxalate Sucrose	Determination of the analytes in food samples	Enzyme immobilization on polymeric membranes Lysine oxidase is immobilized on metallized (Ru/Pd) carbon electrode using electropolymerized poly(*o*-phenylenediamine) H_2O_2 anode oxidation or O_2 cathode reduction Reproducibility < 3% Steady-state response 1–2 min Storage lifetime 1–12 months Analog or RS-262 outputs
Bio Profile chemistry analyzer	No details available	Glucose L-Lactate L-Glutamate L-Glutamine	Determination of the analytes in cell culture and fermentation processes	Autosampling, fully automated O_2 cathode reduction Enzyme–membranes 0.5-ml sample size Imprecision/resolution 5%
Process TRACE 1.2	No details available	Glucose L-Glutamate L-Glutamine	Determination of the analytes in pilot plants and fermentation processes	Flow analysis system with injection Amperometric with sensor chips as biosensors Temperature stabilization, RSD < 1.5% Lifetime > 14 days or 5000 measurements Bioreactors or screen-printed electrodes for several analytes are available on request
Alcohol sensor	No details available	Alcohol Sugars Ascorbic acid Malic acid	Beer and wine; under development	Amperometric disposable, screen-printed electrodes H_2O_2 anode oxidation Selectivity: a polymeric membrane screens out possible interference Response time 3 min
The Answer 8000	No details available L-Glutamate oxidase Alcohol oxidase	Sucrose L-Glutamate Alcohol	Industrial applications	Chronoamperometric measurements at 0.1 V Built-in dilutor (for high concentrations) Biosensor stabilization protocols ensure retention up to 80% of the original enzyme activity after a period of 12 weeks (L-glutamate oxidase) or 25 weeks (alcohol oxidase)
Peroxidase redox polymer kit	Glucose oxidase Acetylcholine esterase/choline oxidase	Glucose Acetylcholine/choline	General applications	Enzymes are covalently bound within a postcolumn reactor (IMER); shipped in cold containers H_2O_2 oxidation at Pt anode at 0.1 V mediated by osmium(III) polyvinylpyridine redox polymer
Microdialysis biosensor by Sycopel	Glucose oxidase Lactate oxidase Glycerol kinase/glycerol-3-P oxidase Acetylcholine esterase/choline oxidase, nonenzymatic L-Glutamate oxidase DD/L-Amino acid oxidase Adenosine oxidase Xanthine oxidase	Glucose Lactate Glycerol Acetylcholine, ascorbate L-Glutamate D/L-Amino acids Adenosine Xanthine	General applications	Electropolymerized poly(*o*-phenylenediamine) is used either as a molecular barrier to electroactive species or to immobilize the enzyme onto the Pt working electrode Ascorbate oxidase is used for the elimination of ascorbate interference Specification for glutamate analysis: linear range 0.5 µM–1 mM Response time 20 s
FAIZA 110-P	No details available	Glucose Lactose Sucrose Galactose Lactate Ethanol/methanol L-Glutamate L-Amino acids	General applications; fermentation process	Flow injection analyzer equipped with the appropriate enzyme cartridge. Response time 3 min Reproducibility < 3% Simultaneous analysis of 6 samples Bioreactor lifetime 1500 runs or 6–12 months depending upon the analyte

(*continued on next page*)

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Table 12 (*continued*)

Instrument	Enzymatic pathway	Analyte	Applied matrix	General comments
LM58 lactate analyzer AM2 industrial alcohol analyzer GM10 industrial glucose analyzer GM7 Micro-Stat multiassay analyzer	Lactate oxidase Alcohol oxidase Glucose oxidase Invertase/glucose oxidase β-Galactosidase/glucose oxidase Glutaminase/glutamate dehydrogenase/NADH/ horseradish peroxidase Glutamate dehydrogenase/NADH/ horseradish peroxidase Alcohol oxidase	Lactate Alcohol Glucose Sucrose Glutamine/ammonia Methanol	Dairy products Beers, wines, consumer products Soft drinks, distilleries, industrial plants Aqueous solutions and extracts Aqueous solutions and fluid Fermentation process Aqueous solutions culture fluid, etc. Fermentation process Soft drinks, colas, and other aqueous products, flat or carbonated	Enzyme-based biosensor, O_2 cathode reduction using a Clark-type amperometric electrode Fluid pumps, peristaltic Sample size 3.5–25 µl depending on the assay Response time 20 s Reagent stability 6–12 months unopened at 0–5 °C Lactate up to 20 mM Alcohol 0–40% v/v Glucose 0–20% w/v Methanol 0–500 ppm Sucrose/lactose up to 50 mM total glucose Glutamine/NH_3 0.5–20 mM
PM-1000, PM-1000DC analyzers; M-100, AS-200 analyzers	No details available	Glucose Sucrose Lactose Lactate Alcohol Glycerin Ascorbic acid L-Amino acids Glutamate Lysine	Food analysis	Enzymatic membranes onto a Clark oxygen electrode Two-point calibration is necessary Sample size 1 to 50 µl; CV 1%
Freshness Meter KV-101	No details available	ATP	Indicator of fish freshness and meat age	Soluble enzymes and a Clark oxygen electrode Sample preparation and extraction are necessary Response time 5–6 min
OLGA, online general analyzer	No details available	Sucrose Glucose Alcohol	Quality control of foods	Automatic calibration, online system based on sequential injection mode Exchangeable biosensors
Enzyme membranes, thick-film biosensor	Glucose oxidase Lactate oxidase Ascorbic acid oxidase β-Galactosidase/glucose oxidase	Glucose Lactate Ascorbic acid Lactose	General applications Provider of some analyzers	Amperometric enzyme sensor Storage stability > 6 months (GOx > 9 months) Operational stability > 10 days or 2000 analysis (GOD > 28 days or 3000 analyses; GOx screen printed > 15 days or 3000 analyses) Linear range: glucose, 0.2–20 mM; ascorbic acid, 0.6–40 mM; lactose 0.1–100 mM
Biosen 5040	Glucose oxidase Lactate oxidase	Glucose Lactate	General applications	Amperometric H_2O_2 anode oxidation Enzymatic membranes Sample volume 20 µl Lifetime 15 days or 3000 analyses Response time 10–15 s Linear range: glucose, 0.5–50 mM; lactate, 0.5–40 mM
PerBaco 2000 PeBaco 2002	Glucose oxidase Fructose dehydrogenase Lactate dehydrogenase Diaphorase/ferricyanide Malate dehydrogenase	Glucose Fructose Lactate Malate	Wine Must	Enzymatic; amperometric Solid binding matrices bearing the biocatalysts Dialysis membranes for preventing interference Dilution and decolorization of the samples is recommended
ASIA flow injection analyzer	No details available	Glucose Alcohol Xanthine Galactose Choline	Quality control of foods and drinks	Automated sampling Wall-jet flow through cell Reproducibility < 1% Sampling throughput 30–120 h Stability 1000 runs per cartridge

Data from Ref. [3].

causes the parasites to go from the mosquito's saliva into a person's blood. *Plasmodium falciparum* is the organism that brings on the most deaths. Peptides containing large amounts of the amino acid histidine are synthesized by *P. falciparum*, which are known as histidine-rich proteins (HRP). One of these is HRP2 and it includes 34% histidine and 37% alanine. In recent years, test kits for the diagnosis of *P. falciparum* malaria based on HRP2 have been most often used [88].

The commercial test kits are based on the lateral-flow immunochromatographic technique. The malaria antigen test works by detecting antigens in the blood that are released by the parasite. A drop of blood is placed in the test buffer solution. The parasite antigen is captured by dye-labeled antibody. The resultant complex is captured on the strip by a band of bound antibody, forming a visible line [88]. The commercial biosensors for malaria are summarized in Table 9.

Other commercial biosensors in clinical analysis

Apart from these commercial biosensors, there are others used for infectious diseases, cancer, and cardiac diseases. Other commercial biosensors in clinical analysis are summarized in Table 10.

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Table 13
Some of the commercial BOD biosensors and their characteristic parameters.

Name	Manufacturer	Type	Measured parameter	Pretreatment	Measurement range (mg BOD/L)	Analysis time	Accuracy
Ra-BOD	AppliTek	Bioreactor	Oxygen consumption	None	20–100,000	30 min	<5%
Biox-1010	Endress + Hauser	Bioreactor	Oxygen consumption	None	5–100,000	3–15 min	3%
MB-DBO	Biosensores	Bioreactor	Oxygen consumption	None	10–1000	30 min	<3%
RODTOX 2000	Kelma	Bioreactor	Oxygen consumption	None	0–500,000	NA	5%
Bio-Monitor	LAR	Bioreactor	Oxygen consumption	None	1–200,000	3–4 min	<5%
BOD 2000 BOD 3000	Nisshin Denki & Central Kagaku Co. Ltd	Biofilm	Oxygen consumption	None	0–500 3–1000	20–40 min	3%
DKK BOD sensor 7842	DKK Corp.	Biofilm	Oxygen consumption	None	0–60	5 min	5%
BODypoint	Aucoteam GmbH	Biofilm	Oxygen consumption	None	5–500	<1 min	<10%
BSBmodul	Prüfgeratewerk Medingen GmbH	Biofilm	Oxygen consumption	None	0–22 or 2–33	3 or < 1 min	<10%
ARAS	Dr. Lange GmbH	Biofilm	Oxygen consumption	None	2–300	1–3 min	<5%
QBOD meter EZ-BOD meter	Bioscience	Respirometer	Oxygen consumption	None	0.5–300 0.5–5000	20 min 15–60 min	10% 5%
RACOD meter	USFilter	Respirometer	Oxygen consumption	None	100–4000 (high) 0–100 (low)	10 min (high) 30 min (low)	NA

Data from Refs. [103,104]. NA, information not available.

Commercial biosensors in food analysis

The food industry requires suitable analytical methods for checking the safety and quality of foods. The determination of chemical and biological contaminants in foods is important to the human health. Apart from contaminants, biosensors are used for other important analytes, such as sugars, alcohols, amino acids, flavors, and sweeteners. Also, in the food industry biosensors mainly focus on analysis of food security (detection of compound contaminants, allergens, toxins, pathogens, additives, etc.), analysis of food composition, and online process control. Quality control is important in the food and beverage industries. In food and fermentation processes, quick, cheap, and safe analytical methods are required to analyze sugars such as glucose, fructose, and sucrose. Also, newer sensor design and construction are important for production processes in high-quality products.

There are many scientific publications on biosensors for food industries; but only a few of them are commercially available and they primarily determine glucose and lactic acid concentrations. Commercial biosensors provide unique solutions for food analysis in terms of specificity and saving time [100]. They are available in different forms, such as autoanalyzers, manual laboratory instruments, and portable systems [101]. The commercial biosensors for food industry are summarized in Table 11.

Selected commercial biosensors in food analysis are summarized in Table 12 [3].

Commercial biosensors in environmental analysis

Environmental pollution is expeditiously increasing owing to global economic expansion and industrial development. Synthetic chemicals, pesticides, and heavy metals are major contaminants in environmental pollution [102]. There are many biosensors under development and also an extensive literature in this area. However, only a small part of all biosensors developed are commercially available.

Commercialized BOD_5 biosensors

Biochemical oxygen demand (BOD) is known as the amount of dissolved oxygen needed by aerobic biological organisms in the presence of organic pollutants during the biochemical degradation of organic matter in water and wastewater. This parameter is one of the most widely used for environmental pollution. The BOD_5 method was accepted in 1936 by the American Public Health Association Standard Methods Committee and is defined as the biological oxygen demand of wastewaters and effluents measured over a period of 5 days at 20 °C. To avoid time-consuming tests, complicated procedures, and unsuitable monitoring procedures, BOD biosensors have been developed and they have an important role in BOD measurement [102].

The first commercial microbial BOD device was produced by Nisshin Denki (Electric) Co. Ltd. in 1983. Currently, a few more BOD biosensors have been developed and put on the market by various manufacturers. Biosensor configurations in both biofilm and bioreactor types are used for BOD_5 measurement [103]. Some of the commercial BOD biosensors and their characteristic parameters are summarized in Table 13. All of them have automatic sample injection and calibration with a standard solution with defined BOD. Ra-BOD (Applitek, Belgium), Biox-1010 (Endress + Hauser, Switzerland), MB-DBO (Biosensores, Spain), and RODTOX 2000 (Kelma, Belgium) are based on three inoculation strategies.

- For Ra-BOD, the measurement bioreactor is continuously inoculated with real sludge from a wastewater treatment plant.
- With the Biox-1010 system, the microorganisms colonize small plastic cylinders inside the bioreactor (to protect them against mechanical abrasion caused by turbulent mixing and to increase the contact surface with the sample being analyzed) before the measurement is performed.
- In the biosensor MB-DBO, the microorganisms first grow in an independent continuous bioreactor, which allows the microbial population to stabilize and feeds the measurement reactor continuously.

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Table 14
Other commercial biosensors for environmental applications.

Instrument	Company	Transducing and recognition element
Biacore	Biacore AB (Uppsala, Sweden)	Optical BI
Ibis	Windsor Scientific Ltd (Berkshire, UK)	Optical BI
SPR-CELLIA	Nippon Laser and Electronics Lab (Japan)	Optical whole cells or macromolecules
Spreeta	Texas Instruments (Dallas, TX, USA)	Optical BI
BIOS-I	Artificial Sensing Instruments (Zurich, Switzerland)	Optical BI
	Amersham International	Optical immunoreagent
	XanTec Bioanalytics GmbH (Münster, Germany)	Optical BI
Kinomics Plasmoon	BioTul AG (Munich, Germany)	Optical BI
IASys Plus	Affinity Sensors (UK)	Optical antibody
Remedios	Remedios (Aberdeen, Scotland)	Optical whole cell
Cellsense	Euroclon Ltd (Yorkshire, UK)	Electrochemical *E. coli*
PZ 106 Piezoelectric antibody	Immunobiosensor system	Universal Sensors (Kinsale, Ireland)
ToxSen	Abtech Scientific, Inc. (Richmond, VA USA)	Electrochemical BI
	Universal Sensors, Inc. (New Orleans, LA, USA)	Electrochemical enzymes
NEC nitrate biosensor	Nitrate Elimination Co. Inc. (Lake Linden, MI, USA)	Amperometric enzyme
eTag assay system	Aclara Bioscience (Mountain View, CA, USA)	Optical eTag reporters
AgriPo II	ApexBio (Taiwan)	Electrochemical

Data from Refs. [105,106].

Table 15
Commercial biothreat/biowarfare tests.

Company	Model	Analyte
ANP Tech, USA	ANP NIDS biothreat/biowarfare handheld assays	*Bacillus anthracis*, SEB, ricin, *Vaccinia*, *Francisella tularensis*, *Coxiella burnetii*, *Brucella*, *Botulinum* toxin A, *Yersinia pestis*, Venezuelan equine encephalitis, *Vibrio cholerae*, *Salmonella*, *Listeria*, *E. coli* O157
ADVNT, USA	BADD	Anthrax, ricin toxin, *Botulinum* toxin, *Y. pestis*, and SEB
Tetracore, USA	Abrin BioThreat Alert kit	—
	Anthrax BioThreat Alert kit	—
	Botox BioThreat Alert kit	—
	Brucella BioThreat Alert kit	—
	Orthopox BioThreat Alert kit	—
	Plague BioThreat Alert kit	—
	Proficiency BioThreat Alert kit	—
	Ricin BioThreat Alert kit	—
	SEB BioThreat Alert kit	—
	Tularemia BioThreat Alert kit	—

Data from Refs. [108–110].

The biosensor BioMonitor (LAR, United States) is based on the bioreactor technology; but this architecture is different from that of the other systems mentioned above. The oxygen consumption is measured in the gaseous fraction of the last reactor of the measurement channel, and the determination of the BOD parameter is calculated from the difference between the oxygen consumptions in the control and the test sample [104].

Other commercialized environmental biosensors

There are commercial biosensors used for environmental monitoring of nitrate, dioxins and dioxin-like compounds, and *E. coli*. The commercial surface plasmon resonance biosensors are successful for environmental monitoring. Biacore AB (Uppsala, Sweden) offers a large range of biosensors. Affinity Sensors (Franklin, MA, USA) produce the IASys line of instruments, which use evanescent-wave technology. Microbial and enzymatic biosensors are used for diagnosis of contaminated land or soil. Other commercial biosensors for environmental applications are summarized in Table 14 [105].

Commercial biosensors for biothreat/biowarfare

Several bacterial and viral agents and toxins can endanger the public health in the event of a bioterrorist or biological warfare attack. Developments in biosensor technology have improved the detection and quantification of chemical and biological warfare agents in real time. These kinds of sensors are a type of biological assay based on immunochromatography that can quickly and accurately identify biothreat/biowarfare agents. The test principle is based on measuring antigen/antibody interactions and, owing to the specificity of antibodies, it can identify the microorganism. Biothreat detection sensors are easy to use and highly accurate [107]. The BioThreat Alert test strip for anthrax is the first commercial antibody test demonstrated worldwide with such specificity [108]. The commercial biothreat tests are summarized in Table 15.

Conclusion and future perspectives

Despite the extensive research performed in the past 2 decades and the clear demand for online measurement, biosensors have been used only in clinical, food, environmental, and biothreat/biowarfare applications.

Most commercial biosensors are focused on clinical applications, such as glucose-detecting biosensors. Other commercial clinical biosensors are used for pregnancy, *E. coli* O157, influenza A and B, *H. pylori*, HIV, tuberculosis, and malaria detection in blood, serum, body fluids, and urine. Research in advanced technologies, including electrodes, immobilization technologies, and nanomaterials supports more reliable, rapid, and accurate detection of diabetes and other diseases such as cancer and cardiac diseases.

The use of biosensors for food analysis can provide a specific, sensitive, rapid, and cheap method for monitoring a range of target analytes. Commercial biosensors are useful for the analysis of food security (detection of compound contaminants, allergens, toxins, pathogens, additives, etc.), analysis of food composition, and online process control. In the coming days the use of commercial biosensors is expected to spread in the food industry.

The increasing number of potentially harmful pollutants in the environment calls for fast and cost-effective analytical techniques. Most of traditional analytical methods (e.g., chromatographic methods) are difficult and need expensive instrumentation and specialized personnel. In this context, biosensors appear to be suitable alternative or complementary analytical tools. Commercial biochemical oxygen demand biosensors are available and have significant applications in aquaculture. These devices are based on microbial transducers and are efficient for online monitoring.

Commercial biosensors are also used for detecting biothreat/biowarfare agents. They provide highly accurate results in the field and in the lab, with results in a short time. Some features, such as accuracy, reliability, ease-of-use, and no need for expensive readers, draw attention.

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There are many biosensors under development and also extensive literature in this area. However, only a small part of biosensors are commercially available, but their commercialization indicates the success of biosensors. Glucose-testing biosensors, pregnancy biosensors, and BOD biosensors are commonly used commercial biosensors. Potential markets for biosensors include food, agriculture, the military, veterinary services, and the environment. The advances observed in biochemistry, chemistry, electronics, and bioelectronics will affect future biosensor production. In the coming days research in biosensor technology is expected to focus on transducer technology and sensing-element development.

Uncited references

[11–33].

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