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Non-invasive sensing for food reassurance

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Abstract: Consumers and governments are increasingly interested in the safety, authenticity and quality of food commodities. This has driven attention towards non-invasive sensing techniques used for rapid analyzing these commodities. This paper provides an overview of the state of the art in, and available alternatives for, food assurance based on non-invasive sensing techniques. The main food quality traits of interest using non-invasive sensing techniques are sensory characteristics, chemical composition, physicochemical properties, health-protecting properties, nutritional characteristics and safety. A wide range of non-invasive sensing techniques, from optical, acoustical, electrical, to nuclear magnetic, x-ray, biosensor, microwave and terahertz, are organized according to physical principle. Some of these techniques are now in a period of transition between experimental and applied utilization and several sensors and instruments are reviewed. With continued innovation and attention to key challenges, such non-invasive sensors and biosensors are expected to open up new exciting avenues in the field of portable and wearable wireless sensing devices and connecting with mobile networks, thus finding considerable use in a wide range of food assurance applications. The need for an appropriate regulatory framework is emphasized which acts to exclude unwanted components in foods and includes needed components, with sensors as part of a reassurance framework supporting regulation and food chain management. The integration of these sensor modalities into a single technological and commercial platform offers an opportunity for a paradigm shift in food reassurance.

Keywords: Non-invasive sensing; food, machine vision; Vis/NIR spectroscopy; UV-Vis fluorescence; hyperspectral imaging, ultrasound; electronic nose; electronic tongue; conductivity; NMR; X-ray; Microwave; Terahertz; quality; reassurance

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Introduction

In recent years, consumers and governments are increasingly demanding information and reassurance on the content as well as on the origin of their food [1-3]. Food industry (suppliers, manufactures and supermarkets) are required to provide and confirm the authenticity and point of origin of food products and their components, in order to protect consumer rights and prevent fraudulent or deceptive practices such as food adulteration. Therefore, food reassurance is crucial to food production and security of food supply [4-6].

Food reassurance

The concept of reassurance relies on the fact that it is desirable to ensure that the food adheres to its implied or commonly understood description. For example, free from inanimate objects such as glass, plastic, metal that can enter through the manufacturing processes; free from unacceptable levels of animate material such as viruses, bacteria, prions and spores that could lead to infection that can enter through poor hygiene; free from unacceptable levels of biological inanimate contamination such as peanut, almonds, contaminated vegetable oil, etc.; corresponds to the packaging claims, including type of food and origin (e.g. British beef). Given that it is best to exclude food contaminants from the food chain, sensors are best deployed in a regulatory context within which the sensing techniques form part of a compliance framework, reassuring that regulation is effective. A strategy for food reassurance might be summarized as Prevent, Reassure, and Detect.

Prevention is the best defense. Detection provides reassurance

Prevention implies a threat to food supply and includes adulteration. Examples of adulteration [7] include horsemeat added to other meats [8], the addition of waste oil to vegetable oils [9], the addition of ethylene glycol in Austrian wine [10] and the addition of melamine to milk in order to increase the apparent protein level [11]. There is also an expectation that a product claiming to be meat does not contain unreasonable levels of fat and gristle.

The best approach to food security is pro-active - anticipate the threat and then prevent it; especially in the manufacturing part of the supply chain with the potential for foreign body contamination from the process line. However, assured prevention requires detection. The rise in food contamination incidents in the UK highlight the need for better detection methods that are

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fast, reliable and economic.

Food incidents need reassurance

The number of food incidents is increasing (See Fig. 1) and the evidence is that this is massively under-reported as food manufacturers have an interest in disguising food recalls which will cost millions of pounds per recall.

Fig. 1.

(1) Foreign bodies: Pieces of metal in food, very often originating from process machinery are a common cause of complaint. Pieces of glass, plastic, bone and nut shell are other common contaminants. Other common foreign body contamination is insects (dead or alive - in which case this can be regarded as infestation), 'natural' plant materials, hair and fiber.

(2) Chemical contamination: Herbicide and insecticide contamination, particularly from organophosphates continues to be a threat to human health. Other examples include mercury pollution of the sea around Japan [12] giving rise to unacceptably high mercury intakes for some populations relying on a fish diet. The Fukushima accident has also increased the threat of radioactive contamination of food [13] and in the UK, arising from the 1986 Chernobyl reactor explosion and up to 2012 sheep from a number of farms in North Wales, Southern Lake District and near nuclear facilities in Scotland were banned from human consumption [14].

(3) Infestation: A large proportion of food spoilage arises due to insect and other forms of infestation such as rodents.

(4) Food deterioration: Food may deteriorate as a result of poor storage and/or transport. For example, chocolate may bloom if stored at too high a temperature, a fatty spread may separate into water and oil. Fruit and vegetables may ripen to the point of unacceptability and may also become bruised or damaged in some other way.

(5) Counterfeiting of food: High value foods such as Iberian Ham are subject to extensive counterfeiting [15].

(6) Food borne disease: Food borne disease is one of the biggest causes of ill health and time off work [16].

Globalization of food supply need reassurance

This is contradictory because the globalization of food supply has led to a diversification and

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in some ways an increase in food security, at least in some countries such as the UK. Arguably globalization of food supply is also a cause of food poverty in the less industrialized countries. The threat addressed here is that it is much more difficult to provide reassurance of food origin, authenticity and safety in a global food chain. Large multinationals can mitigate the risk through control of every stage in the process from the seed, through planting, fertilizer and herbicide/insecticide, harvesting, distribution even as far as controlling the produce on the supermarket shelf. The Bernard Matthews Turkey scandal illustrates the potential for public health impacts arising from the globalization of food supply. Waste meat imported from Matthew's plant in Poland was contaminated with Bird Flu and was intended for feeding to Turkey's in the UK [17]. Bovine Spongiform Encephalopathy (BSE) was also likely caused by the feeding of contaminated beef to cows [18].

Non-invasive sensing shows promise for food reassurance

Common food reassurance methods, such as immunological and enzymatic techniques, DNA and protein based assays and triacylglycerol analysis as applied in laboratories [19-21] are usually capable of detecting low levels of adulteration, but they are expensive, invasive, sophisticated, laborious, and technically demanding [22, 23].

Recently, non-invasive (NIV) rapid sensing techniques combined with multivariate data analysis show promise for food reassurance. Because NIV techniques do not permanently alter the food being inspected, they are highly valuable techniques that can save both money and time in reassurance. In comparison with these reported common methods [19] which are time-consuming, expensive, use harmful reagents, need expert laboratory staff and are strongly dependent on rigorously following a standardized protocol to obtain accuracy, non-invasive rapid sensing techniques are non-destructive, require only basic training in a user-friendly software, a few minutes for detecting and processing and no cost at all excluding initial instrument and software purchase. This is the major stimulant for continuous ongoing developments in the field of NIV. There have been continuously increasing research efforts in the last two decades according to the increasing number of publications in NIV

Although there are many complete reviews of non-invasive techniques, the great volume of recent research results in this field requires a constant update. In this article, we review non-

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invasive techniques and normal chemometrics for food assurance. The techniques are organized according to physical principle rather than quality attribute, because some measurement techniques can be used to measure widely different quality attributes. The advantages limitations, and future trends of the techniques will be reviewed.

Techniques employed for non-invasive food assurance

There are many non-invasive sensing techniques in food as shown in Fig.2. Among the techniques used, NIV techniques are mainly based on physical methods of analysis except biosensors. Some NIV techniques such as machine vision can provide external information such as color, shape, size, and the absence of surface defects of food products [24], and some NIV techniques such as ultrasound can provide internal quality such as firmness and crispiness, taste, aroma, and absence of internal defects [25, 26]. NIV techniques such as the electronic nose [27] and hyperspectral imaging [28-31] can give quality attributes such as freshness, safety, nutritional value and health-promoting properties, chemical residues. Looking at the enormous number of literature produced during the last fifteen years, two groups of methods: optical methods, (visible/near/mid-infrared spectroscopy and imaging) and acoustic methods, (ultrasound spectroscopy, imaging and passive acoustics), may be considered the most researched non-invasive techniques for the assurance of food.

Fig. 2.

Optical techniques

Physical methods often rely on electromagnetic waves (Fig. 3). A complex interplay between absorption and scattering of the electromagnetic waves (light) guides the light - food interaction. There are three basically different ways of obtaining signal from a sample by measurement of diffuse reflection (I_{fd}), Transmission (I_t), and Emission (I_e). I_{fd}, I_t, and I_e contain information about absorption and scattering of light in food. Therefore, they may give information regarding the structure and chemical component related information in food. For example, IR/NIR/MIR scattering are related to the microstructure of the cells and intra/extracellular environments and the C-H, O-H, and N-H bonds of the main compounds (water, carbohydrates, fats/oils and proteins) are responsible for the absorption.

Fig. 3.

Photons are most strongly scattered by structures with the same size as the photon

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wavelength, and can be absorbed only if they have the right energy to excite the vibrational states of the molecule in food. Most food is opaque to radiation in ultra-violate (UV), visible (Vis), near-infrared (NIR) and infrared (IR) regions of the electromagnetic spectrum. In this region, the main optical techniques are Vis/NIR spectroscopy, UV-Vis fluorescence, machine vision, hyperspectral imaging, and Raman spectroscopy. Published applications of these techniques to food are too numerous to record comprehensively here, particularly covering the last thirty years.

Machine Vision

When consumers buy food, food perception is limited to visual perception. The external appearance of food is a very important quality for both consumer and producer. Machine vision (MV), or computer vision, that can give the visual sensation of food, is therefore an important food assurance technique. It consists essentially of a digital camera that is connected to a computer and software for image analysis. MVs in visible light regions could recognize size [32], shape [33], color [34, 35], and texture [36] of food. Some machine vision systems are also able to inspect these objects in parts of the electromagnetic spectrum invisible to humans, such as X-ray [37], ultraviolet (UV) [38], near-infrared (NIR) [39], and infrared (IR) [40]. It is growing at a fast pace due to recent advances in hardware and software [41-43]. There are extensive reviews about machine vision applications to food [44-47]. The potential of machine vision in the food industry has long been recognized and the food industry is now ranked among the top 10 industries using this technology [47, 48].

Vis/NIR spectroscopy

The light in Vis/NIR region can penetrate quite deeply (up to a few centimeters, depending on the wavelength) into biological tissue, as the absorption by water is relatively low in the Vis/NIR range compared to the mid-infrared (MIR) ranges [49] and the scattering of the light in this region is significantly larger than in MIR, this enables light to diffuse in the sample volume and to be reemitted at the tissue boundaries [50-52]. Therefore, Vis/NIR spectroscopy can produce fingerprint spectra for food assurance. Usually, advanced chemometric techniques are needed to extract information from these spectra. Vis/NIR spectroscopy has been used successfully to authenticate many foods such as fruit [53, 54], vegetable [55, 56], meat [57, 58], fish [59], vine [60], milk [61], starch [62, 63], oil [64-66], cereal [67], transgenic food [68], and others. It also successfully gives physical-

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chemical parameters of food, such as freshness [69, 70], water content [71, 72], soluble solids contents [73, 74], acidity [75-77], firmness [77-79], texture [80-82], and others, that relate to quality and safety of foods. There are many reviews of this area in recent years [66, 68, 83-92].

UV-visible fluorescence spectroscopy

Fluorescence spectroscopy is able to determine several properties (functional, composition, nutritional) without the use of chemical reagents. UV light excites the electrons in the molecules of certain compounds in food and causes them to emit lower energy light. As molecules of compounds in food can drop down into any of several vibrational levels in the ground state, the photons emitted will have different energies and thus frequencies. Therefore, analyzing the different frequencies of light emitted in fluorescent spectroscopy, along with their relative intensities, makes it possible to ensure food contains particular fluorescent compounds e.g., tryptophan, heterocyclic aromatic amines in meat [93, 94].

Front face fluorescence is always used for food samples, as they are opaque. As the species excited depend on the excitation wavelength, it is worthwhile noting that fluorescence is a selective method. There are some important wavelengths for intrinsic fluorescence spectra of compounds in food, such as aromatic-amino-acids, nucleic-acids (excitation: 250 nm, emission: 280-480 nm), tryptophan residues (excitation: 290 nm, emission: 305-400 nm) of proteins and NADH (excitation: 336 nm, emission: 360-600 nm). These intrinsic fluorescence spectra can be considered as fingerprints of food [94]. Karoui and Blecker (2011) provided an overview of fluorescence spectroscopy measurement for the quality assessment of food systems [93]. The application of fluorescence spectra has been successfully investigated for the quality of animal (i.e., dairy [95, 96], meat [94, 97], fish [48, 98, 99], and egg [100]) and vegetable (oils [101], cereal [102], sugar [103], fruit and vegetable [96, 104-106]) products as well as the identification of bacteria [95, 107, 108] of agro-alimentary interest.

However, foods are complex products containing numerous fluorescent compounds. In such cases the signals of the different chromophores may overlap, and it becomes more complicated for food assurance.

Hyperspectral imaging and multispectral imaging

Spectral imaging (i.e., hyperspectral and multispectral) has the capability to rapidly and non-

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invasively monitor both physical and morphological characteristics and intrinsic chemical and molecular information of a food product for the purpose of assurance. During the last decade, spectral imaging has developed rapidly as a better tool for safety and quality inspection of various foods as it integrates conventional imaging and spectroscopy to attain both spatial and spectral information from an object [109, 110]. Hyperspectral images are usually used as fundamental datasets from which to determine optimal wavebands that can be used by a multispectral imaging solution for a particular application [111]. Systems within 400-1000 nm were mainly used for fruit and vegetables, because they are generally cheaper than those within 900-1700 nm and are less influenced by water[112, 113].

Combining different image acquisition methods (e.g., reflectance/transmittance and reflectance/fluorescence) can give hyperspectral/ multispectral imaging systems more inspection capabilities than systems that use only a single imaging mode [114]. Such image acquisition combinations along with data fusion techniques are likely to expand in the future for building multitask food inspection systems. There are many recent published reviews dealing with the application of Vis/NIR hyperspectral/ multispectral imaging for classification and grading [115, 116], defect [117-119] and disease [120] detection, distribution visualization of chemical attributes [121, 122], and for inspection of meat [123, 124], fruit [110, 125, 126] and vegetable [110, 127, 128], fish [129, 130] and et al.

Raman spectroscopy

Raman spectroscopy can obtain detailed chemical information on a sample without the need for labeling and almost insensitive to water. It is also a non-invasive technique that yields reliable results for solid and liquid multicomponent food samples [131]. In a typical Raman analysis of food, the fingerprint of Raman spectra information can be used to identify a molecule of interest in complex food matrix as the assignment of Raman-scattering bands to corresponding vibrational modes of molecules is integral [132, 133]. In addition, the changes in chemical composition or molecular structure of food can be monitored by intensity of frequency shifts of specific vibrational modes. Raman spectroscopy has a high potential in food assurance.

Raman spectroscopy has good application prospects in food quality for its spectra are not extremely sensitive to polar materials such as water [131 134]. Raman spectroscopy for the study of molecular vibrations and structure of the chemical composition of heterogeneous foods and food ingredients may be combined with FT-IR [135]. Raman spectroscopy has been successfully applied for characterizing olives [136], juices [137], fruits [138], and analyzing wax [139], fatty acid [140], protein [141] et al in food, and investigating structural and texture [142] information of food. Raman spectroscopy is an advanced technique that enhances the vibrational spectrum of molecules adsorbed on or in the vicinity of metal particles and/or surfaces.

Summary of optical techniques

Optical techniques are applied over a wide range of length scales, from planetary to microscopic and are of many types. Optical radiations propagate well in the air, optical spectroscopy can be used without contact. The interaction between the optical radiation and the sample under test can be assessed by measuring either the reflected, transmitted, scattered or diffused light, or several of these parameters. Optical instrumentation may be quite inexpensive and easy to miniaturize allowing the development of portable devices suitable for industrial applications. Optical spectroscopy is rapid, ease to use, versatile and inexpensive; it is one of the most powerful analytical techniques among the non-destructive measuring techniques. For these reasons optical techniques have become the most widespread non-destructive measuring techniques for food reassurance, such as meat, vegetable, fruit and food productions. The typical detection results of optical techniques are shown in Fig. 4 taking meat as an example (adapted from the literature [143-147]).

Fig. 4. [143-147]

Acoustical techniques

Quality and acceptability of food products are often assessed based on the sounds produced during crushing or biting of the food [148]. At present instrumental acoustic methods (especially low power ultrasound) are becoming more and more popular for the investigation of food product properties because they are relatively cheap, simple and energy saving. Sound is transmitted through a food product to obtain the acoustic characteristics of the product used for food assurance. Some crisp food may be considered unacceptable and of poor quality for example when little sound is produced during breakage [149]. Acoustic Envelope Detector for crispness assessment of biscuits [150]. Crispness assessment of roasted almonds by an integrated approach to texture

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description: texture, acoustics, sensory and structure [151]. It is also used for monitoring the composition and physicochemical properties of food components and products during processing and storage, which is crucial for controlling the food properties and improving its quality.

From Fig. 5, by selecting the appropriate frequency range, sound can be utilized in many industrial applications including food [152]. Sound propagates through food materials as mechanical waves causing alternating compressions and decompressions [153]. These sound waves have characteristic wavelength, velocity, frequency, pressure and period. The interaction of sound waves with matter alters both the velocity and attenuation of the sound waves via absorption and/or scattering mechanisms [154].

Fig. 5.

For acoustic techniques, there are main four measurements instruments, microphone measurement technique, pulse-echo ultrasound technique, pitch and catch technique, and resonance techniques as shown in Fig. 6.

Fig. 6.

Acoustical techniques have been utilized for non-invasive analysis and monitoring of fresh vegetables and fruits in both pre- and postharvest, cheese during processing, commercial cooking oils, bread and cereal products, bulk and emulsified fat based food products, raw and fermented meat products, fish and poultry, food gels, aerated and frozen foods. Other applications include the detection of honey adulteration and assessment of the aggregation state, size and type of protein [155].

Scanning acoustic microscopy and ultrasound imaging are the two main acoustic imaging techniques to form images of detection objects. In a scanning acoustic microscope a focused ultrasound beam is coupled into the sample and the returning back scattered signal analyzed in a variety of ways, including simple pulse echo [156, 157]. Ultrasonic imaging (ultrasonography) is a medical technology that has long been used as a diagnostic technique. The same probe that transmits the pulse listens for scattered waves to produce echo signals that are processed to form images. This technique has found several applications in food technology, such as the pulse-echo ultrasound has been used to detect defects in food packaging seals using [156]. Recently an airborne ultrasound technique has been used in food quality detection.

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Electrical techniques

The interest in electrical characteristics of food materials has been associated with non-destructive measuring techniques for many years [158]. As simple, rapid and non-destructive measuring techniques, dielectric properties used in the detection of processing condition or the quality of food. This technique is especially useful for detecting moisture content in foods as permittivity and moisture can be closely correlated when water content is high. In microwave thawing, it is very sensitive to the rates and uniformity of heating in partially frozen food material [159]. The measurement is rapid and it does not destroy the substance; it is therefore suitable for on-line assurance of food quality [94, 160].

By using two electrodes to induce a current flow (I) and a voltage (V) between these two electrodes, it possible to deduce an electrical impedance by applying Ohm's law, $V = ZI$. This is the most elementary and commonly used method and apparatus for detect food quality. The impedance (Z) is a complex function of alternating current frequency f, e.g. $Z = Z_{\mathrm{real}} + iZ_{\mathrm{imag}}$, where Z_{real} is the real part (resistive), Z_{imag} the imaginary part (capacitive) and $i = (-1)^{1/2}$ [94].

As most of food tissue is biomass, when an electric current passes through food tissue, it passes through the extracellular fluid (ECF) or through both the ECF and intracellular fluid (ICF) compartments [161]. The current pathway is generally represented as two parallel branches: one through the ECF and the other through the capacitive membrane and the ICF compartment. The extracellular pathway is considered to be purely resistive, whereas the intracellular pathway including the capacitive effect of the cell membrane is an impedance (i.e. complex), with a resistive part (real) and a capacitive part (imaginary), resulting in the magnitude of the intracellular impedance being frequency dependent [162].

Conductivity plays a fundamental role in food assurance measurements [163-167]. The conductivity of a food is generally measured by passing a known current at constant voltage through a known volume of the material and by determining resistance. The electrical conductivity of foods has been found to increase linearly with temperature, and water/ionic content.

Electrical permittivity is another parameter which can be used to characterize the dielectric property of food. It depends on dielectric constant ε′, which is related to capacitance of a substance and its ability to store electrical energy, and the dielectric loss factor ε″, related to

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energy losses when the food is subjected to an alternating electrical field i.e., dielectric relaxation and ionic conduction [168]. The permittivity can be related to chemical composition, physical structure, frequency, and temperature, with moisture content being the dominant factor [169].The ratio of dielectric loss factor to dielectric constant (ε″/ε′) is called the loss tangent (tanσ) or dissipation factor, a descriptive dielectric parameter [169].

Various factors influence the dielectric properties of food materials such as frequency of the applied alternating electric field, moisture content, bulk density, temperature [94, 159]. At constant temperatures, dielectric constant (ε′) and loss factor (ε″) of food materials increase with decreasing frequency. The penetration depth (PD) decreased with increasing frequency, temperature and moisture content [159, 169]. At higher microwave frequencies only salty foods show an increase in ε″ with temperature but at lower microwave frequencies there is a general increase in ε″ [169]. Both ε′ & ε″ of various foods increased with increasing moisture content. For fruits and vegetables [170, 171], ε′ increases with temperature, whereas ε″ increased with increasing temperature and ε′ increased with temperature at lower frequencies, but decreased with temperature at the higher frequencies. For beef or meat [172], both ε′& ε″ increases with decreasing frequency at constant temperature; however, ε′ decreases and ε″ increases with increasing temperature at constant frequency. For fish, a sharp increase in dielectric properties was observed around the freezing point [173]. Both ε′ & ε″ increased with increased water content at constant temperature; ε′ & ε″ of lean tuna were larger than those of fatty tuna. ε′ of marinated catfish and shrimp, generally decreased with increasing temperature whereas ε″ increased with temperature. Both ε′ & ε″ of fish meal increased non-linearly with moisture content and also increased with temperature in a relatively linear manner [174-176].

The interest in dielectric and electric properties of food materials has historically been associated with the design of electrical equipment. As shown in Fig. 7 (a), the simple detection devices only need a low frequency generator, a couple of electrodes and a view meter. It is a convenient method for evaluating food quality, especially for detecting moisture content in foods. However, in this bipolar system, electrode polarization can produce a systematic error in the voltage measured between the two electrodes caused by parasitic capacitive impedances occurring at the interface of the two electrode-sample ohmic contacts [168]. To eliminate this electrode-sample

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contact effect, a tetrapolar measurement method can be deployed using two injection electrodes in which voltage is measured via two separate measurement electrodes. Another way is to use several aligned, regularly spaced electrodes and take bipolar measurements between each pair of electrodes. To avoid dispersion in measurement caused by influencing factors (such as temperature), normalized methods, such as ratio of impedances at two frequencies (1 kHz/100 kHz), index of anisotropy, et al, are frequently used. Fig. 7 (b) shows a circular multi-electrode sensors based on anisotropy index methods which was successfully used in meat aging detection [164]. S. N. Jha et al [159] has given a detail review which covers theoretical aspects of different electrical properties, their measurement techniques, applications of dielectric properties in agriculture/food processing sector for quality and safety assessment in food processing. Electrical and dielectric apparatus has been applied for determination of various characteristics of food such as frost sensitivity, chilling and freezing tolerance, moisture content, seed germination, mechanical stress, pasteurization and other properties of grains, seeds, meat, sugar, milk, wood, soil, fruit and vegetable, infected food (moisture content, maturity of fruit, freshness of eggs, potential insect control in seeds, radio frequency heating) [94, 161, 162, 165, 166, 176-182].

Fig. 7.

X-ray techniques

As shown in Fig.8, the wavelengths of X-radiation (composed of X-rays) are shorter than those of UV rays and longer than those of gamma rays. X-rays have a wavelength in the range of 0.01 to 10 nanometers, corresponding to frequencies in the range 30 petahertz to 30 exahertz and energies in the range 100 eV to 100 keV. X-rays with photon energies above 5-10 keV (below 0.2-0.1 nm wavelength) are called hard X-rays, while those with lower energy are called soft X-rays [183, 184].

Fig. 8. [186]

Since Röntgen discovered them in 1895, X-rays are widely used to image the inside of objects by using their penetrating ability [185]. FDA (US Food and Drug Administration) recommend that the maximum dose permitted for irradiation of spice is 30 kGy. Different applications use different parts of the X-ray spectrum are shown in Fig.8. Food applications mainly use soft X-rays.

X-rays that are elastically or inelastically scattered from a sample provide valuable

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information about the internal characteristics of a sample such as the molecular structure, density and atomic number [187, 188]. There are four techniques for quality and safety control of food based on X-rays. Firstly, the transmission imaging measurement, such as 2-dimensional radiography well-known from medicine or the line scan method producing images when the product passes through a vertical plane of X-rays used for foreign bodies detection in food [183, 189-191]. Secondly, X-ray microtomography for microstructural measurement [192-194]; Thirdly, X-ray fluorescence spectroscopy measurement, such as X-ray fluorescence spectra for determination of trace elements in food [195-198]; and fourthly, small angle measurement for the structure analysis of food component, such as the structure of proteins, allergens, starches, and et al [199-203]. Among these four techniques, X-ray transmission imaging measurement techniques are widely used in the food industry.

Conventional X-ray transmission imaging measurement technique as shown in Fig. 9 (a) has long been used for online detection of foreign bodies in food products relying on the absorption contrast between the foreign body and food product. As X-rays penetrates a food product, it loses some of its energy. A dense area, such as contaminant, will reduce the energy even further. As the X-rays exits the product, it then reaches a sensor. The sensor then converts the energy signal into an image of the interior of the food product [204]. Foreign matter appears as a darker shade of grey that helps to identify foreign contaminants. The X-rays transmission inspection system, as shown in Fig. 9 (b), (c), mainly comprises a computer-controlled X-ray generator (i.e. X-ray source tube), a line-scanning sensor for X-ray detection, conveying belt, stepping motor, image-acquisition card and computer.

Fig. 9.[185].

Foreign bodies are a major reason for consumer complaints in the food industry. The application of good manufacturing practice and hazard analysis throughout the whole food supply chain is the most effective way to prevent and reduce contamination and thereby protect consumers. X-rays have strong penetration ability, so the image can directly reflect internal defects of food and agriculture products, and structural organization changes in quality. X-ray transmission imaging measurement techniques have great potential in detecting the internal quality of animal products, and has been widely used in the food industry for the inspection of food quality and safety.

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For the meat industry, the principle of operation of X-ray measurement systems is that various components of muscle-lean meat, fat, and bone-have different properties when exposed to physical energy from X-rays. The relative density is the critical property, as lean tissue has a consistent density of 1.07 to 1.08, whereas fat varies depending on the temperature. Skin has a similar density to lean meat, which means that collagen measurement is hardly possible. As materials attenuate X-rays depending on their energy, use can be made of the selective attenuation of one, two, or more energy levels; that is, mono, dual (DEXA), or multiple energy X-ray absorptiometry (MEXA) [205-207]. Some internal disorders with negative effects on quality that should be detectable by X-ray techniques include cork spot, bitter pit, water core, and brown core for apple, blossom and decline, membranous stain, black rot, seed germination, and freeze damage for citrus, and hollow heart, bruises, and perhaps black heart for potato [56, 191, 208, 209], where the aim is to analyze internal elements that are undetectable to the naked eye. Because the method is primarily dependent on the density of the tissue, not the chemical composition, the selectivity is limited. X-rays have not yet been used to their fullest potential in a range of application areas, especially the agricultural and food industries. Zwiggelaar, Reyer, et al. [183] applied X-rays imaging to detection of perspex, a soft plastic, and cellulose in a water environment as a simulation approach in food and agricultural products. They also indicated possible applications of these techniques within the agricultural and food industries, such as foreign-body detection, quality control and food processing [183]. McFarlane, N. J. B., et al examined constraints on foreign body detection in food by using Compton scattered X-rays. The detection of a 4 mm glass fragment in water, instant coffee and muesli using Compton scatter was demonstrated by experiment [210]. Mery, Domingo, et al developed an X-ray machine vision approach to automatically detect fish bones in fish fillets (Fig. 9 (d)) [185]. Nielsen, Mikkel Schou, et al [189] present a novel approach for detection of organic foreign bodies such as paper and insects in two food products using X-ray dark-field imaging with a grating interferometer.

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI)

Nuclear magnetic resonance (NMR)

NMR is based on the emission and absorption of energy in the radiofrequency range of the electromagnetic spectrum [211]. All nuclei that contain odd numbers of protons or neutrons can be

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observed with NMR. Nuclear magnetic resonance techniques have been used for examining agricultural products from the biological and physiological points of view since the mid-1950s; however small sample sizes and slow data processing have limited the usefulness of these studies in terms of in-line sorting. With the development of large magnets for medical applications, a variety of new types of magnets and radio frequency coils have become available for use in engineering applications of NMR [212]. The most commonly measured nuclei are ^{1}H and ^{13}C, although nuclei from the isotopes of many other elements can be observed (^{23}Na, ^{31}P, etc.). NMR is sensitive to the existence of mobile water, oil, and sugar, which are major components of agricultural materials. Therefore, owing to its non-invasive nature, NMR has a high potential for use in internal-quality evaluation of agricultural products whenever a component of the product contains an NMR sensitive nuclei that is correlated with quality. NMR spectra can also be considered as a type of a fingerprint for a product that carries qualitative and quantitative information on the composition [211].

(1) ^{1}H NMR is a better spectroscopic method for assessing water holding capacity (WHC), intra muscular fat (IMF) and total water content in porcine muscles than visual, fluorescent and near infrared (NIR) reflectance spectrophotometry. As water protons are easily visible with ^{1}H NMR, this technique is obviously especially useful for studying water in food products. The parameters linked to vegetable, fruit, meat and fish products are numerous: water content, WHC, water distribution (i.e. water state) [213], water mobility, etc. In additional, ^{1}H NMR can identify variations in water-protein interactions and then in protein states, so it is a potential tool for studying structure. It has been shown that NMR parameters are highly sensitive to differences in the muscle structure of farmed and wild cod and to the effect of brine injection, brining, and rigor tension on the muscle.

(2) ^{31}P NMR is mainly applied to post mortem evaluation in meat and fish muscle. ^{31}P NMR is used in the prediction of fish freshness, of WHC in rabbit muscle, in association with ^{1}H MAS and NMR [214].

(3) ^{13}C NMR spectroscopy has been successfully used for detection of sugars and acids and that ^{13}C resonances of amino acids can be used as fingerprint for the monitoring of wines. Proton and ^{13}C NMR data have been used for the differentiation of white wines coming from three

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German regions [211, 214, 215].

(4) ^{23}Na NMR is performed to quantify salt content in meat and fish products. For instance, in association with ^{23}Na MRI, it is a rapid and reliable alternative for optimizing and understanding industrial salting processes in the fish industry [216].

Magnetic resonance imaging (MRI)

Similarity to the NMR, MRI is also a nondestructive, nonintrusive spectroscopic technique based on the interaction of electromagnetic radiation in the radiofrequency range with matter. MRI is particularly suitable for biological materials (given that protons are abundant therein), mainly in water, but also in fat, oil, or salt, and it allows one to distinguish these components [217]. Furthermore, MRI is sensitive to several quality parameters affecting the produce, particularly those that affect the water concentration or mobility (e.g., internal browning).

MRI has been used successfully in the past to measure several quality parameters of fresh fruit and vegetables, including the presence of internal defects, such as chilling injury in micro-tom tomato [218], watercore development in apples [219], postharvest ripening of tomato [220], microporosity in fruit [211]. MRI has also been used to measure physical properties, such as size, shape and volume, and has been correlated with firmness, soluble solids, or acid content [221-223]. MRI has been also used successfully to measure several quality parameters of meat and meat products. An original experimental approach has been developed based on the quantitative, local, dynamic and in situ analysis deformation and water content of chicken during cooking [224]. MRI has been used to detect the water distribution [225], viscoelastic properties [226] and muscle structure [227] in meat.

Compared to other techniques such as X-ray imaging, MRI image acquisition speed is relatively low, and is strongly determined by the required image quality and whether 1D or 2D imaging is performed [212]. In Fig. 10 CT and MRI images of a healthy apple and one with severe water core symptoms—a disorder characterized by water-soaked regions in the fruit—are compared. The affected regions are clearly visible in both images, although the imaging principle is very different: In CT, the contrast between healthy and affected tissue is due to the increased density in the latter due to the water soaking; in MRI, the affected area lights up because the water mobility is very different from that of healthy tissue. MRI shows large potential for online grading,

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sorting, or quality evaluation of fresh produce [212].

Fig. 10. [217].

Microwaves and terahertz waves

Microwaves

In North America, only four microwave and three radio frequencies are permitted by the Federal Communications Commission (FCC) for dielectric heating applications (Decareau, 1985). The allotted microwave frequencies are 915, 2450, 5800MHz and the radio frequencies are 13.56, 27.12, and 40.68MHz [228]. The interest in the dielectric properties of food has been principally for predicting heating rates describing the behaviour of materials. The relevant quality attributes that can be assessed with the structure, composition (particularly water content), water state and water distribution in the product, and particularly water content profiles [229]. In the high frequency range the dielectric properties of food are closely correlated with water state and water content. Dielectric relaxation spectroscopy determines the response of the molecular motion of polar molecules in the sample to a weak external alternating electric field [230]. As the frequency of the electric field is increased, it reaches a frequency called the relaxation frequency when the polar molecule can no longer rotate with the electric field. Dielectric properties change significantly around this relaxation frequency [231].

The rare industrial applications currently using microwave are based either on cavity, antenna or probe measurements. A specific method using transmission-reflection measurements should be highlighted. The basic configuration of this method uses two antennas, one transmitting and one receiving, the meat streaming on a conveyor belt between the two non-contacting antennas [232]. Applications of microwave sensors in other sectors of the food industry could be adapted for the meat industry, particularly for measuring water content. Work has been carried out over the last two decades by the US Department of Agriculture on water content, water state and density of grain and seed [233], and meat [231].

Terahertz

Terahertz (THz) radiation, or THz wave, is an electromagnetic wave whose frequency lies between mid-infrared and microwave radiation. Unlike X-rays, terahertz waves are not harmful, so there are no exposure worries for practitioners or patients. Moreover, THz waves have the

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properties of penetration for various materials, low photon energy, and sub-millimeter spatial resolution. Therefore THz spectroscopy has received considerable attention as a nondestructive inspection method. In particular, this low photon energy method is suitable for food inspection with active substances [234, 235]. Due to the high absorbance of THz radiation by water, the most widespread application of THz spectroscopy would seem to be for quantification of total moisture content in foods. [236]. At the same time, THz radiation interacts only very weakly with materials composed of non-polar molecules, such as plastics and ceramics and is reflected by most metals [236, 237]. This indicates the THz technology has the potential for detection of some foreign material in food [238]. A transmission continuous-wave (CW) THz imaging system using reflecting mirrors is illustrated schematically in Fig. 11 [239].

Fig. 11. [239]

One demonstration of THz imaging for foreign body detection in foods has been reported, for the detection of contaminants in chocolate. Due to its high fat and low moisture content, chocolate is relatively transparent to THz energy. When foreign objects, such as glass or plastic, are placed in chocolate, they alter the scattering profile of a transmitted THz wave and are thus detectable. Foreign bodies (glass, stone and metal) were concealed within the interior of a bar of chocolate and THz images of the contaminated sample were obtained using a raster scanning Thz-TDS system operating in transmission mode. It was possible to identify foreign bodies in the chocolate sample, both in the presence and absence of its plastic foil packaging [236]. THz-TDS in transmission mode was used for the characterization of the dielectric properties of oil-water complexes with water content ranging from 0.43 to 3.28%. This enabled determination of the absorption coefficient and refractive index of the samples, and thus determination of the amount and structure of water in these complexes. The results indicated the formation of a hydrogen bonded oil--water complex, rather than dissolved water clusters in the oil-water complexes . The developed system was employed for simultaneous determination of the sugar and alcohol content of commercial alcoholic beverages independent of other properties such as colour, organic matter content, carbonation and flavor [240]. Common packaging materials made from cardboard and polymers are transparent to THz radiation. This makes THz spectroscopy and imaging attractive tools for quality validation of packaged products [241]. THz spectroscopy may also be used to detect

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pesticide in food powders (sticky rice, sweet potato, and lotus root) [242], antibiotic in milk [242] and egg powder [243], the characteristic optical properties in vegetable oil (sunflower, peanut, soybean and rapeseed oil) [244],

Although THz waves are useful for food inspection, a few researchers have reported many drawbacks [245]. One of the limitations of THz spectroscopy for moisture content detection is that it is not suitable for high moisture products of thickness greater than 1 mm. This is due to the high absorption of THz radiation by water. Another challenge facing practitioners of THz spectroscopy is the effect of physical variations in a sample (e.g. particle size) on the refractive index of a material. This is particularly pertinent in the case of quality monitoring of fresh produce which shows high variability in this respect. Scattering effects may adversely affect measurements of THz absorption in certain materials. When the grain size of solids is comparable to the THz wavelength, extinction spectra are severely influenced by scattering losses.

Biosensors techniques

Electronic nose and electronic tongues

The electronic nose (e-nose) was developed in order to mimic human olfaction that functions as a non-separative mechanism: i.e. an odor (Fig. 12). An odor stimulus generates a characteristic fingerprint (or smell-print) from the sensor array. The sensor array consists of broadly tuned (non-specific) sensors made of a variety of odor-sensitive biological or chemical materials. The patterns or fingerprints are used to construct a database and train a pattern recognition system so that unknown odors can subsequently be classified and identified. The detection system of e-noses usually consists of an array of chemical gas sensors or biosensors (i.e., sensors that incorporate a biological sensing element). For chemical gas sensors, a variety of different sensor types have been developed, in which three types of materials are commonly used: metal oxides semiconductors (MOS) [246], conducting polymers composites and intrinsically conducting polymers. Recently, new technologies such as optical sensors [247], gas sensitive field effect transistors [248] and quartz microbalance (QMB) sensors [249] and ion mobility spectrometry (IMS) [250] have entered this field.

Fig. 12. [41].

Similarly to an e-nose, electronic tongues (e-tongues) can be also considered as analytical

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instruments which simulate the human senses. The e-tongue devices are composed of a sensor array coupled to chemometric processing used to characterize complex liquid samples. Although the e-tongues works in liquid media, such as the biological tongue, the sensitivity of the artificial system can be much higher, and its capabilities much wider; this makes the performance of the e-tongues closer to that of the olfactory system. In fact, the e-tongues can be thought of as an analogue to both olfaction and taste senses and can recognize the flavour of liquid or liquefied products. The e-tongue can also be used for quantitative detection of a variety of dissolved compounds, including volatile substances that are responsible for odours but originate from either the liquid or solid phases.

E-nose and e-tongue are composed of three elements: (i) sampler component, (ii) array of chemical sensors with different selectivity, and (iii) software with the appropriate algorithm to process the signal and get the results [251]. Another common feature of all e-nose and e-tongues systems is, therefore, the utilization of an array of nonspecific sensors together with data processing by pattern recognition methods. Once the data from the individual sensors from the array is collected, the e-nose systems require a suitable post processing procedure to analyze and classify the data. Pre-processing of multivariate signals in sensor arrays represents an essential part of the measuring system. Again, similar to biology, one of the most often used data-processing methods is an artificial neural network (ANN) the algorithms of which are based on modelling of learning and recognition processes in the human brain [252]. Other data processing techniques such as principal component analysis (PCA), linear discriminate analysis (LDA), partial least squares (PLS), functional discriminate analysis (FDA), cluster analysis (CA), fuzzy logic are also widely used for processing of the data from multi-sensor systems. Among these techniques, PCA, PLS, LDA, FDA and CA are based on a linear approach while fuzzy logic, ANN and PNN are regarded as nonlinear methods [251, 253].

The strengths of both the electronic nose and tongue include high sensitivity and the fact that they are easy to build, cost-effective and provide a short analysis time. Therefore, these devices are becoming more and more popular as objective automated non-destructive techniques to classify and recognize of a large variety of foods, such as meats [254, 255], vegetable [256], fishes [257, 258], juice [259, 260], beverages [261], oil [262] and wines [263].

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Colorimetric sensor array

E-nose systems have a distinct advantage over most other gas detection technologies as it allows non-destructive method to detect odour. However, it also has a number of disadvantages, including poor detection sensitivity at low compound concentration relative to their vapor pressure and poor discrimination between compounds; the latter proves especially problematic in interference from the large environmental changes in humidity and acidity. Recently, a new artificial olfaction technology based on a colorimetric sensor array is used for odours and volatile organic compounds (VOCs). This colorimetric sensor array comprises thin films of chemically responsive dyes on porous membranes. The array of multiple dyes, whose colors change according to the full range of intermolecular interactions, provides enormous discriminatory power among odorants in a simple device that can be easily digitally imaged. The chemically responsive dyes are usually Porphyrins, metallo-porphyrins, phthalocyanine and pH indicator.

Normal electronic nose systems generally allow for distinction between analytes of different chemical functionality, the discrimination of compounds within similar chemical compounds remains a challenging goal. Previous array technologies for such electronic noses generally rely on multiple, cross-reactive sensors based primarily on changes in properties (e.g., mass, volume, conductivity) of some set of polymers or on electrochemical oxidations at a set of heated metal oxides. Specific examples include conductive polymers and polymer composites, polymers impregnated with a solvatochromic dye or fluorophore, mixed metal oxide sensors, and polymer-coated surface acoustic wave devices. For the colorimetric sensor array, it relies on bond formation, acid-base interactions, hydrogen-bonding, dipolar and multipolar interactions, p-p molecular complexation, van der Waals and physical adsorption interactions between sensor and analyte. This is believed to be a fundamental flaw in the development of chemical sensors with both high sensitivity and high selectivity [264, 265].

A colorimetric sensor array system is depicted in Fig. 13. Gas streams (N_2) containing the vapors of interests were generated by flowing nitrogen through the sample chamber in a thermo-stated, glass-fritted bubbler. Digital mass-flow controllers were utilized to control nitrogen flow speed. The ‘before’ image was first acquired on the flatbed scanner; an array was then exposed to a flowing stream of N_2 containing the analytes of interest, and the array was then scanned again

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after equilibration. Experiments were run until full equilibration was demonstrated by comparison of repeated scans. The response of the array is mass transport limited; interaction times (ligation, proton transfer, etc.) are much faster than the typically observed array response. Under proper conditions of rapid gas flow, equilibration of the array occurs within 2 min, even at ppmv analyte concentrations; under static diffusion conditions, equilibration (especially with low volatility analytes) can take 1 hour more, depending of course on the specific cell configuration. Color-difference maps were obtained from the scanned RGB images by digitally subtracting the image before exposure to analytes from the image after exposure, using a 314-pixel average from the center of each pigment spot (thus avoiding subtraction artifacts at the periphery of the spots) as follows (Fig.13) [266].

$$\Delta R = \left| R_a - R_b \right| \tag{1}$$

$$\Delta G = \left| G_a - G_b \right| \tag{2}$$

$$\Delta B = \left| B_a - B_b \right| \tag{3}$$

Here, *a* represent after, *b* represent before. ΔR, ΔG, ΔB are the color-difference.

Fig. 13.

This colorimetric sensor array is not sensitive to humidity and temperature due to the hydrophobicity of the sensor materials and sensors plate [264, 267]. It is superior to traditional MOX gas sensor techniques in the analysis of solid and liquid samples aroma. Therefore, the colorimetric sensor array can act as a fingerprint for food assurance. Usually, advanced chemometric techniques are needed to extract information from these color-difference maps. The colorimetric sensor array has been used successfully to detect many foods such as evaluation of meat [268, 269] and fish freshness [257, 270, 271], discrimination of wine [272, 273], vinegar [274-276], coffee [277], sugar [278] and tea [279, 280].

The previous sections have described sensing odours using an artificial olfaction but this is a significant technical challenge. In recent years, instead of attempting to reproduce human odor impression, most commercially available instruments have other application areas. Table 1 gives an overview of electronic noses on the market according to the criteria above, listing their manufacturers and technology basis [281].

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Table 1. Commercially Available Electronic Noses (adapt from Röck, Barsan, and Weimar [281])

manufacturer	no. of systems sold	model	technology
Agilent, http://www.chem.agilent.com/		4440A	quadrupole fingerprint mass spectrometry
AIRSENSE Analytics, http://www.airsense.com/	180	i-PEN	gas sensor array
		PEN3	gas sensor array
		GDA 2	IMS, PID, EC, 2 MOX sensors
Alpha MOS, http://www.alpha-mos.com/	500	FOX 2000	6 MOX sensors (or QMB/CP)
		FOX 3000	12 MOX sensors (or QMB/CP)
		FOX 4000	18 MOX sensors (or QMB/CP)
		Gemini	gas sensor array
		Kronos	quadrupole fingerprint mass spectrometry
		Heracles	2 capillary columns (1-3 m) and 2 FIDs
		RQ Box	EC, PID, MOX sensors
		Prometheus	MS and 18 MOX sensors
AltraSens, http://www.altrasens.de/		OdourVector	6 sensors
AppliedSensor, http://www.appliedsensor.com/	>100 000	Air Quality Module	2 MOX sensors
Chemsensing, http://www.chemsensing.com/			colorimetric array
CSIRO, http://www.csiro.au/		Cybernose	receptor-based array
Dr. Foedisch AG, http://www.foedisch.de/		OMD 98	2×6 sensors
		OMD 1.10	2×5 MOX sensors
Draeger, http://www.draeger-safety.com/		Multi-IMS	ion mobility spectrometry
		MSI150 Pro2i	ECs
Electronic Sensor Technology, http://www.estcal.com/		ZNose 4200	GC and SAW
		ZNose 4300	GC and SAW
		ZNose 7100	GC and SAW
Environics, http://www.environics.fi/	9000	M90-D1-C	ion mobility spectrometry
Forschungszentrum Karlsruhe, http://www.fzk.de/		ChemPro100	ion mobility spectrometry
Gerstel GmbH & Co. KG, http://www.gerstel.com/		SAGAS	8 SAW sensors
GSG Mess- und Analysengera¨te, http://www.gsg-analytical.com/		QCS	3 MOX sensors
Illumina, http://www.illumina.com/		MOSES II	modular gas sensor array
Microsensor Systems Inc., http://microsensorsystems.com/		oNose	fluorescence sensorssbead array
		Hazmatcad	SAW
		Hazmatcad Plus	SAW array and EC
		Fuel Sniffer	SAW
		CW Sentry 3G	SAW and electrochemical sensor array
		SAW MiniCAD mk II	2 SAW array
		VaporLab	GC and EC
Owlstone Nanotech, Inc., http://www.owlstonenanotech.com/		Tourist	field asymmetric ion mass spectrometry
		Lonestar	field asymmetric ion mass spectrometry
Proengin, http://www.proengin.com/		AP2C	flame spectrophotometer
		TIMs detector	flame spectrophotometer
		ChemRAE	ion mobility spectrometry
RaeSystemes, http://www.raesystems.com/		UltraRAE	separation tube and PID

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		Eagel monitor	GC and EC
		AreaRAE monitor	PID, 2 ECs, 1 catalytic bead sensor, O2 sensor
		IAQRAE	PID, NIRD CO2, EC, polymer-capacitated humidity sensor, thermistor, humidity-temperature sensor
RST-Rostock, http://www.rst-rostock.de/		FF2	6 MOX, *T*, humidity
		GFD1	6 MOX, *T*, humidity
Sacmi, http://www.sacmi.eu/		EOS 835	gas sensor array
		EOS Ambiente	gas sensor array
Scensive Technologies Ltd., http://www.scensive.com/	<100	Bloodhound ST214	14 conducting polymers
ScenTrak, http://www.cogniscentinc.com/			fluorescent dye
SMart Nose, http://smartnose.com/	250	SMart Nose 2000	quadrupole fingerprint mass spectrometry
Smith Group, http://www.smithsdetection.com/		Cyranose 320	gas sensor array
		IONSCAN	ion mobility spectrometry
		SENTINEL II	
		CENTURION	ion mobility spectrometry
		GID-2A	ion mobility spectrometry
		GID-3	ion mobility spectrometry
		SABRE 4000	ion mobility spectrometry
		ADP 2000	ion mobility spectrometry
		CAM	ion mobility spectrometry
Sysca AG, http://www.sysca-ag.de/		Artinose	38 MOX sensors
Technobiochip, http://www.technobiochip.com/		LibraNOSE 2.1	8 QCM sensors

Abbreviations: MOX: Metal oxide sensors, CP: conducting polymers sensors, GC: gas chromatography sensors, QCM: quartz crystal microbalance sensors, SAW: surface acoustic wave sensors, PID: Photo ionization detectors, EC: electrochemical conductivity sensors

Integrating non-invasive sensors

Integrating non-invasive sensors from farm to table

There are many factors that influence the quality of food from the farm to table, such as agro-processing, time, handling procedure, environmental conditions and the processes which they undergo. In each of these steps, the quality of food needs to be monitored and controlled. Non-invasive sensors can illuminate these steps and address the important issue of “traceability” in global trade. Sensors may be deployed on satellites, on drones, on robots, on towers and close to the production line as shown in Fig. 14.

Fig. 14.

From space, satellite remote sensing, such as hyperspectral imaging and microwave imaging, can provide key information in near-real time over large areas, such as monitoring climate change impacts on agriculture, monitoring global crop and natural vegetation conditions, guiding the pesticide and irrigation on crops, et al [282, 283]. From the air, drone aircrafts with spectrometers, airborne sound sensors, microwave sensors, et al, can used in precision farming in land or

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greenhouse, that is to adapt the application of input factors (e.g. nitrogen or pesticides) to the current demand of the plant, and adapt management based on the given growing conditions (for example seeding based on soil moisture) [284, 285]. For a robot worked in greenhouse and factory or at line, non-invasive sensors are viewed as the “eyes”. The sensors guide the actions of robots. For example, for an unattended function automatic milking systems (AMS) require extensive sensor systems. These are necessary for identifying and monitoring cows, for monitoring technical equipment and for teat location, as well as for assessing the udder and the product quality [286-291].

A vision of the future

Advances in laboratory instrumentation have made it possible to integrate a variety of sensors for insuring food quality and safety. However, the transfer of the promising, and in many cases proven techniques to industry is taking place at a slow pace. Hence, there are great opportunities for non-invasive sensing to be commercialized. For example an integrating sensor on robots in a greenhouse could be used with:

- Passive acoustic sensors to detect small mammal and insect activity,
- With aid of sensor integration and data processing reposition sensors to accurately locate and correctly identify activity,
- If the activity is a threat, robots ‘herd’ the targets using power ultrasound,
- Once confined to a small area, the targets are then removed. This could remove the need for spraying an entire store or field and provide a faster and economic response to infestation.
- Microwave sensors on towers map mobile water in fields and greenhouses.
- Combining data from many sensors creates “New ways of seeing”.

Conclusions and future trends

This review article covers different non-invasive sensing techniques such as Machine vision, NIR spectroscopy, hyperspectral imaging, Raman spectroscopy, electronic nose, ultrasound, magnetic resonance imaging technique, X-ray, and Terahertz, with their basic concepts & principles and their applications. Table 2 shows the main features of nondestructive techniques for food assurance. The advantages and limitations are also outlined. Non-destructive evaluation techniques provide information on product properties such as discontinuities and separations;

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structure; dimensions and metrology; physical and mechanical properties; composition and chemical analysis; stress and dynamic response; signature analysis and et al. As computers become ever more powerful non-invasive sensing techniques in assessment and evaluation of food samples is becoming more popular. All these techniques are complementary, meeting the needs of ever growing consumer expectations and can be considered the tools for a future food industry and market. They can make direct measurements on samples and provide multi-parametric information suitable to be treated online to improve the decision-making of customer.

Table 2.

Understanding the best way to evaluate food samples is of vital importance to the food scientist [282]. For external attributes such as color, size, and absence of external defects, techniques such as machine visions, spectral imaging, are now widely used on commercial sorting lines. For internal quality attributes, there are also several techniques available, such as spectroscopy, ultrasound, X-ray, and nuclear magnetic resonance. These techniques measure a complex signal that needs to be related to the quality attribute of interest via chemometric techniques. Some techniques such as NIR spectroscopy require frequent recalibration. For flavor of food, the emerging technology of electronic nose and electronic tongue based on the biosensors are also available commercially. The success of techniques for food assurance often depends critically on how their measurement principle mimics the way humans assess a particular property. Future sensor designs would, therefore, preferably be based on biomimetic principles.

From the sensing research viewpoint, the key challenges in the development of non-invasive sensing for food reassurance devices are the improvement of signal-to-noise ratio (SNR) and sensitivity, development of wearable continuous non-invasive systems, evaluation of analytical performance, development of procedures for highly precise food reassurance determination, and reducing the time taken for food reassurance measurement. The signal-to-noise ratio (SNR) and the sensitivity of non-invasive sensing for food reassurance devices can be improved by employing next-generation of transducers and methods that can do the parallel monitoring of multiple parameters. Although all the results presented in this review seem to be very promising, in our opinion these devices are still in an early stage of development, especially biosensors techniques, and much more research has to be carried out in order to implement them in the

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process production. Major concerns include the lack of intermediate precision studies (i.e. using different operators or instruments) and long term studies, more validation studies and higher number of analyzed samples being required in some cases to extract more reliable conclusions. Scientists are now trying to use sensor technology in every aspect of life so that considerable efforts are given to improve the performance of the non-invasive sensing and reduce the cost of production. Other practical issues such as sensor surface contamination, drift of responses and calibration stability have also to be addressed. It is also very important to develop portable and wearable instruments, and that involves great reduction in energy requirements and power consumption and makes it desirable to miniaturize equipment.

From the food industry and market viewpoint, firstly, for methods to be useful to the industry, they should be rapid, easy to operate, widely accepted, so that different companies use the same methods and therefore know what the other side in the buyer-seller relationship has been measuring; comparable to and even better than current evaluation methods. All the techniques used in this review are essentially non-invasive. Whether they will become widely accepted by the food industry remains to be seen. The costs of labour and training of assessors are likely to increase and the cost of instrumentation such as the image analysis is set to decrease dramatically. Consumer and governmental pressures for better description of quality and traceability of food products will also increase. Secondly, portable and wearable non-invasive will bring many exciting opportunities for food assurance applications. With the entry of big multinational companies, including food industry (such as Nestle), supermarkets (Tesco), internet companies (Google), and several smaller sensing companies, the nascent field of wearable and portable, non-invasive sensing is expected to grow rapidly, with new innovative devices entering the consumer market in the coming years.

From the technique viewpoint, firstly, for each non-invasive technique, there are still lots of challenges. For example developing time- and space-resolved spectroscopy for more accurate measurements of quality attributes of food than NIR spectroscopy, improving hardware and software so that real-time X-ray tomography and MRI become available for reasonable costs, reducing drift and improving reproducibility of electronic noses with improved sensor designs for aroma measurements, et al. Secondly, a multi-sensor device food assurance with a combination of

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instrumental techniques (electronic noses, spectroscopic methods, texture-meters, image analysers, colour meters and devices measuring electrical properties) is a challenging but potentially rewarding problem. This will enable and facilitate comparison and evaluation of the techniques, by minimizing the problem of biological variation and the effect of different handling of the food. The combination (fusion) of outputs of different instrumental techniques has emerged as a means for increasing the reliability of classification or prediction of foodstuff specifications as compared to using a single analytical technique [283].

Finally, integration of radiofrequency identification or Bluetooth devices with non-invasive sensors will enable users to wirelessly transmit data to their cellphone/computer in a more user-friendly fashion. Such real-time monitoring devices will enable a more comprehensive assessment of the food quality. A wide variety of new non-invasive sensing devices are thus expected to be introduced for the food industry and market in the near future.

Table 2 the main features of non-destructive techniques for food assurance.

Class	Technique	Analyte	Speed	Penetration depth*	Cost	Application modes	Disadvantages
Optical techniques	MV	Color, size, shape; surface defects	fast	Surface	Cheap to moderate	Lab, portable, commercial	Low chemical information
	IR/NIR spectroscopy	Component, active ingredients physical attributes	fast	Several mm	moderate	Lab, portable, commercial	Susceptible to moisture, single point, requires training
	UV/UVF	Chemical components, defects, spoilage	fast	Several mm	moderate	Lab, portable, commercial	Influence by lighting and other chemical, , requires training
	Raman	Component, active ingredients, physical attributes	fast	Several mm	high	Lab, portable	Insensitive to polar materials, expensive, requires training
	MSI/HSI	Chemical components and distribution, physical attributes	fast	Several mm	Moderate to high	Lab, portable	Large dataset, requires training
Acoustical techniques	Sound	Internal physical attributes	fast	several cm	Cheap	Lab, portable	Limited to acoustics impedance
	Ultrasound	Internal physical attributes chemical composition	fast	several cm	moderate	Lab, portable	
Nuclear magnetic	NMR/MRI	Internal chemical composition, distributes	slow	several cm.	high	Lab	Expensive equipment
Radiation	Soft X-ray	Internal disorders	Fast	several cm	Moderate	Lab, commercial	Hazardous, not applicable to bulk flowing products
	Dual X-ray	Density, thickness, chemical composition	Fast	several cm	high	Lab	
Electrical techniques	Conductivity	Physical attributes, moisture	Fast	several cm	Cheap	Lab, portable	Requires training
	Dielectric properties	Physical structure, chemical composition	Fast	several cm	cheap	Lab, portable	
	Micro waves	structure, composition (particularly water content)	Fast	Several cm	Cheap	Lab, portable, commercial	Susceptible to moisture
	Terahertz	Component, active ingredients physical attributes	Fast	several cm	high	Lab	
Biosensor	E-nose	Odur composition	Fast	-	moderate	Lab, portable	Require training
	E-tongue	Taste composition	Fast	-	moderate	Lab, portable	
	Colorimetric sensor array	Odur composition	Fast	-	cheap	Lab, portable	Require data base

* : Penetration depth of the techniques for meat

Abbreviations: MV, machine vision; IR/NIR, infrared/near infrared; UV/UVF, ultraviolet and ultraviolet fluorescence; MSI/HIS: multispectral and hyperspectral imaging; NMR/MRI, Nuclear magnetic resonance and Magnetic resonance imaging; E-nose/E-tongue, electronic nose and electronic tongue.

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Glossary

ANN: artificial neural network;CA: cluster analysis;CP: conducting polymers sensors;EC: electrochemical conductivity sensors;E-nose/E-tongue: electronic nose and electronic tongue;FDA: functional discriminate analysis;GC: gas chromatography sensors; IR/NIR/MIR: infrared/near infrared; LDA: linear discriminate analysis; MOX: Metal oxide sensors; MSI/HIS: multispectral and hyperspectral imaging; MV: machine vision; NMR/MRI: Nuclear magnetic resonance and magnetic resonance imaging; PCA: principal component analysis; PID: Photo ionization detectors; PLS: partial least squares; QCM: quartz crystal microbalance sensors; SAW: surface acoustic wave sensors; SERS: Surface enhanced Raman Spectroscopy); UV/UVF: ultraviolet and ultraviolet fluorescence; NIV: non-invasive; THz: Terahertz.

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Figure captions:

Fig. 1. Incident by category 2006 and 2012 UK, Adapted from ESP KTN "Sensing in Food" workshop report 25th February 2014.

Fig. 2. Non-invasive sensing techniques in food assurance.

Fig. 3. The light–food interaction and the electromagnetic spectrum (adapted from Google image).

Fig. 4. Typical detection results from optical techniques used in meat detection. (Abbreviations: MV: machine vision, NIR: near infrared; UV: ultraviolet and ultraviolet fluorescence; HIS: multispectral and hyperspectral imaging.) [143-147]

Fig. 5. Approximate frequency ranges corresponding to sound, with rough guide of some applications.

Fig. 6. Acoustic techniques, (a) microphone,(b) pulse-echo, (c) pitch and catch, (d) resonance techniques.

Fig. 7. A handled device for impedance measurement with two electrodes (a) and a multidirectional sensor (b).

Fig. 8. Different applications use different parts of the X-ray spectrum (adapted from Wikipedia [200], we added some soft X-ray applications).

Fig. 9. Principle of X-rays transmission radiography (a) and soft X-ray inspection system (b) picture, (c) schematic diagram, (d) X-ray image of fish fillets in which the fish bones are detectable [199].

Fig. 10. X-ray CT (*left*) andMRI (*right*) images of Ascara apples without (*a*,*b*) and with (*c*,*d*) water core. Both techniques are capable of detecting the water core region inside the fruit; however, the contrast in the MRI images is better due to the particular pulse sequence used. Figure reprinted from Herremans et al. (2014) with permission from Elsevier. Abbreviations: CT, computed tomography; MRI, magnetic resonance imaging [230].

Fig. 11. Transmission CW THz imaging system based on the parabolic mirrors operating at 0.2 THz using a pyramidal horn antenna located in front of the sample (adapt from Kim, G., et al.) [239].

Fig. 12. Schematic representation of the components of an electronic nose [41].

Fig. 13. The diagram of colorimetric measurement. A, B, C: three-way valve, During the

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measurement, three different phases could be distinguished: concentration, measurement and cleaning. The electro-valves, controlled by a computer program, guided the N_2 through different circuits depending on the measurement phase.

Fig. 14. Sensors, sensor deployment and length scales.

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Fig. 1.

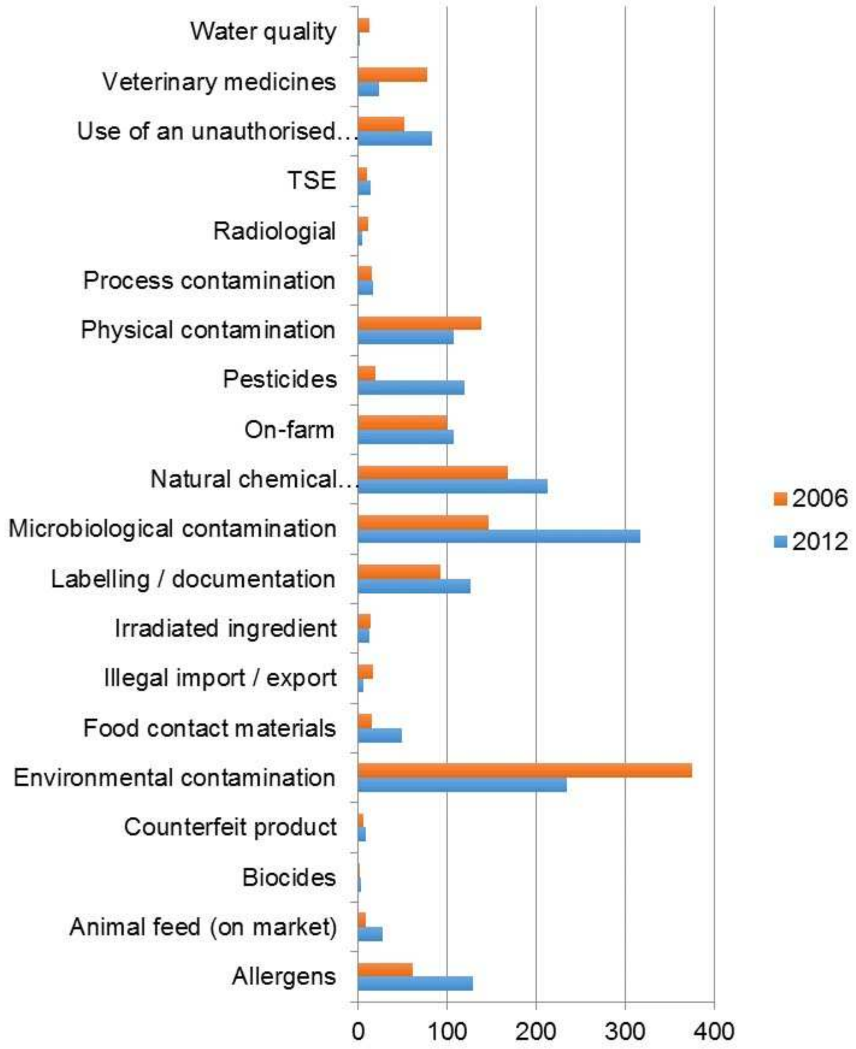

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Fig. 2.

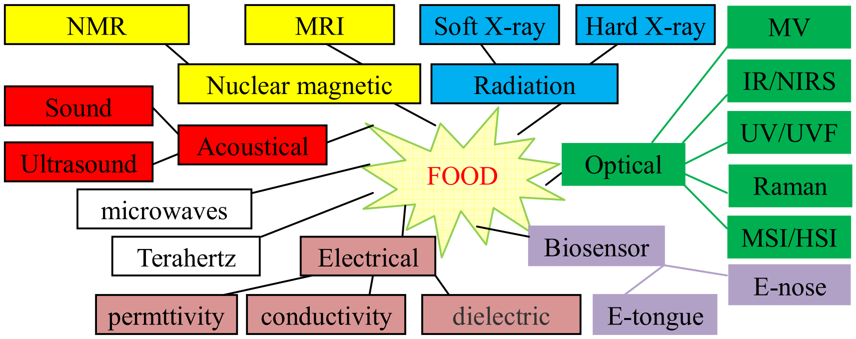

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Fig. 3.

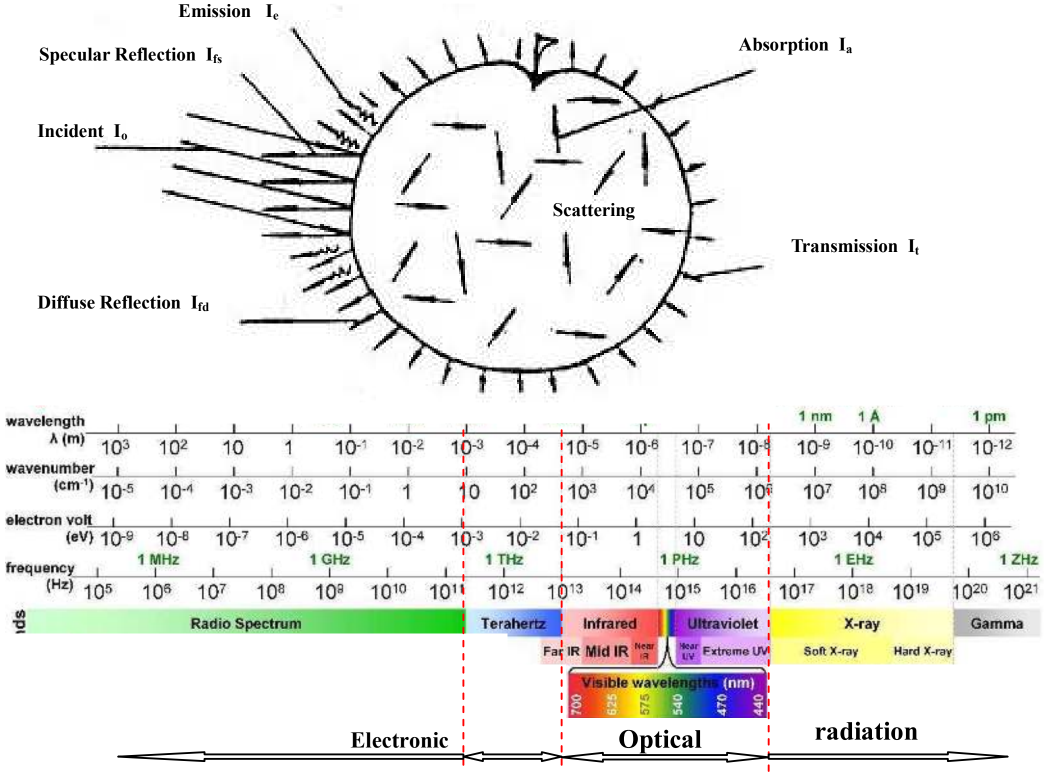

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Fig. 4.

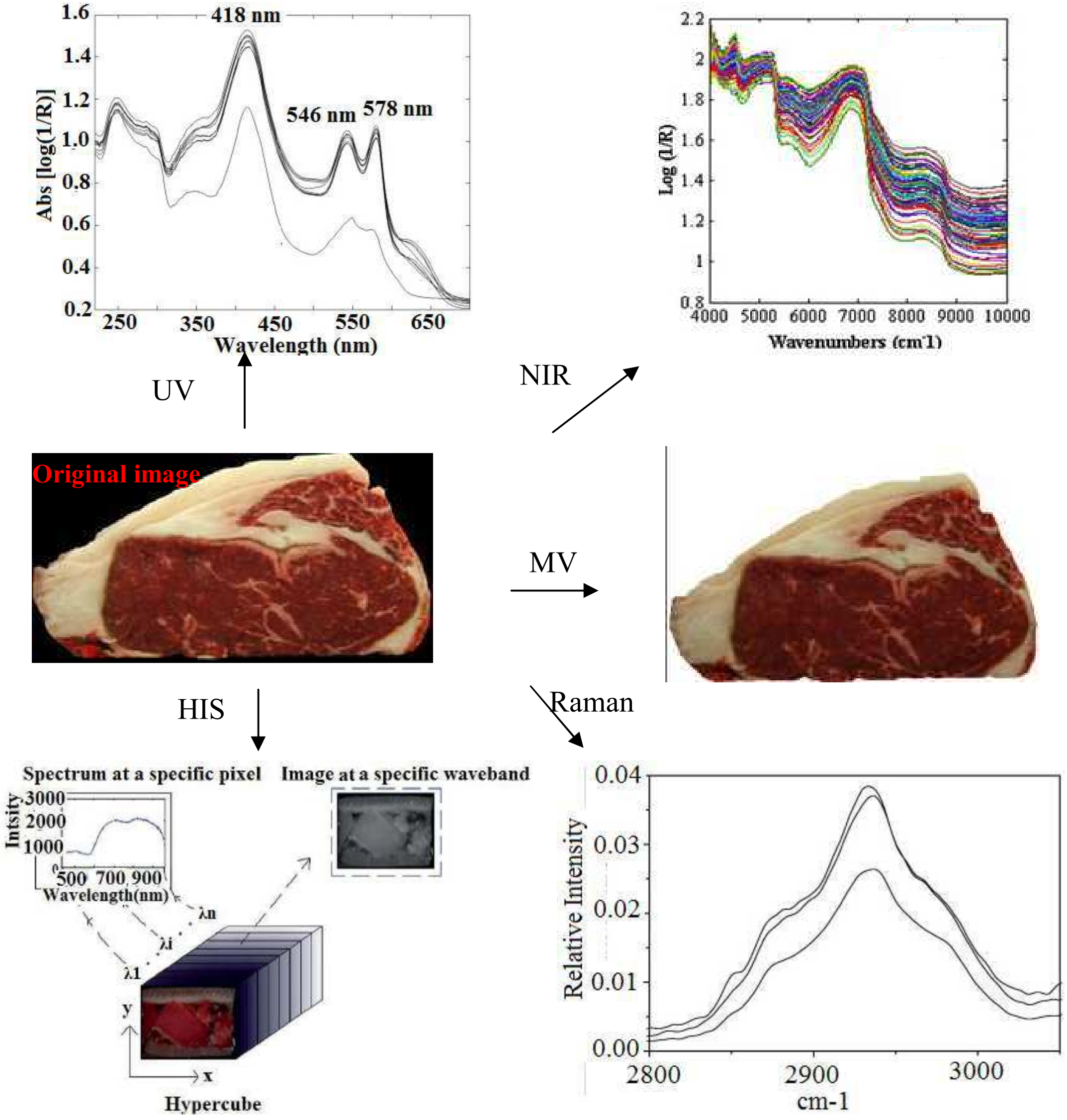

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Fig. 5.

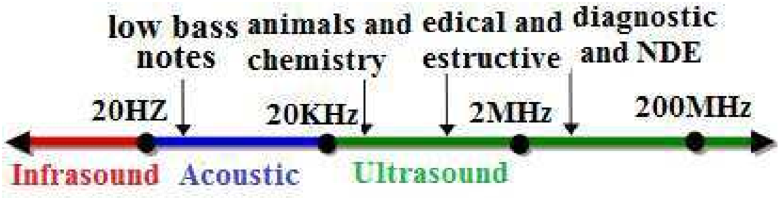

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Fig. 6.

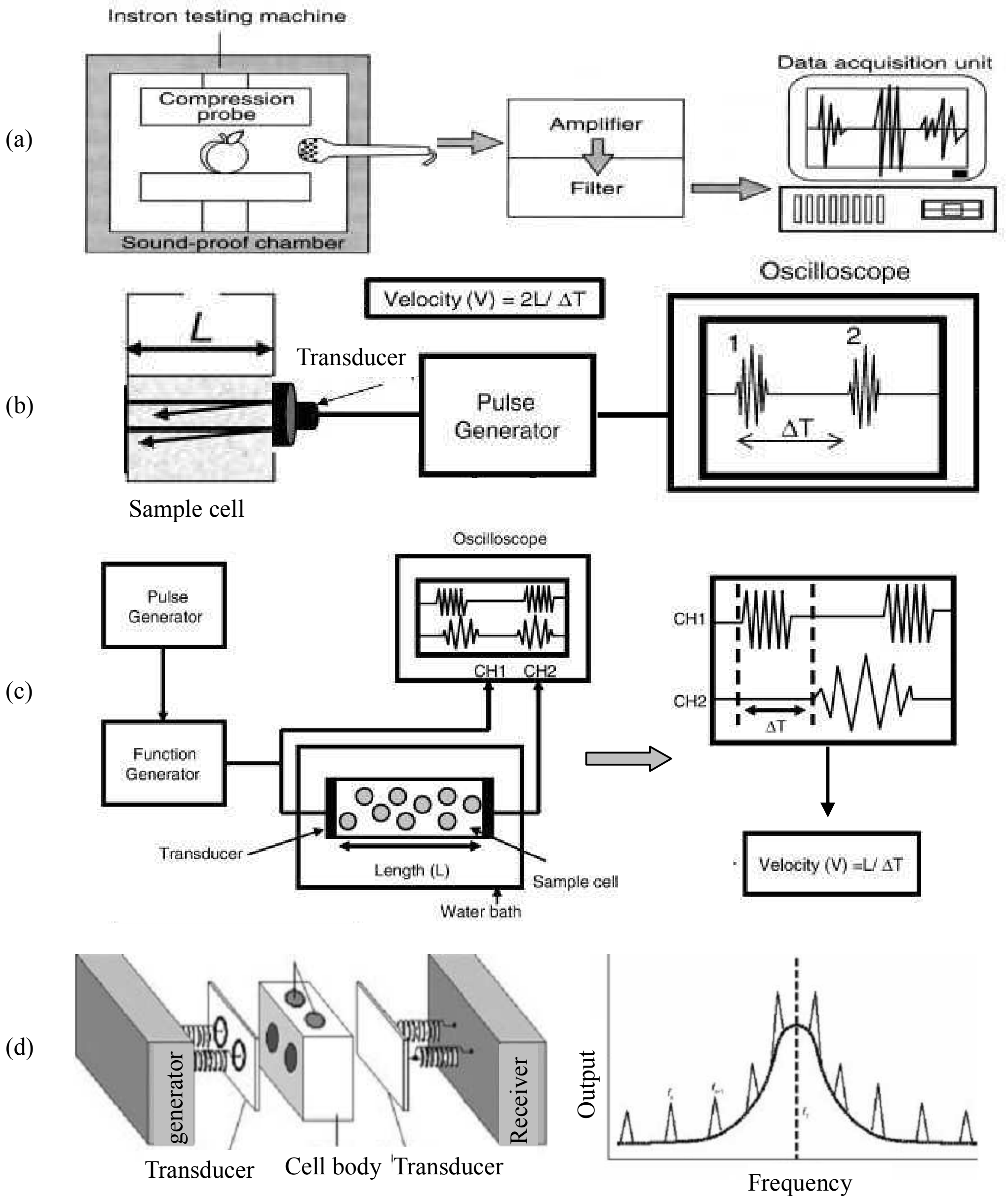

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Fig. 7.

(a) (b)

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Fig. 8.

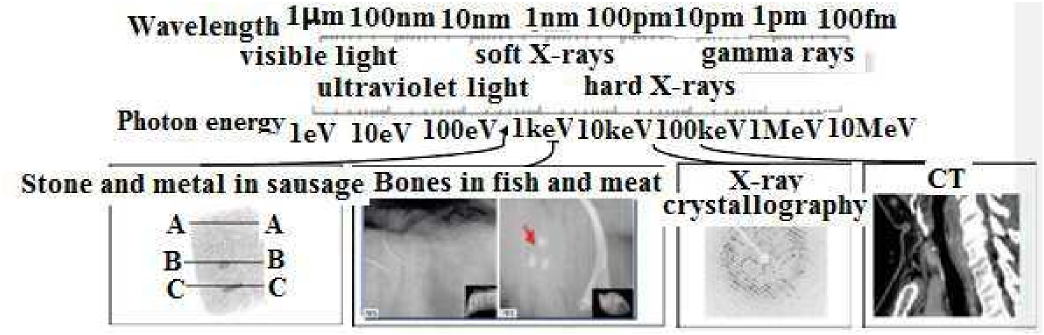

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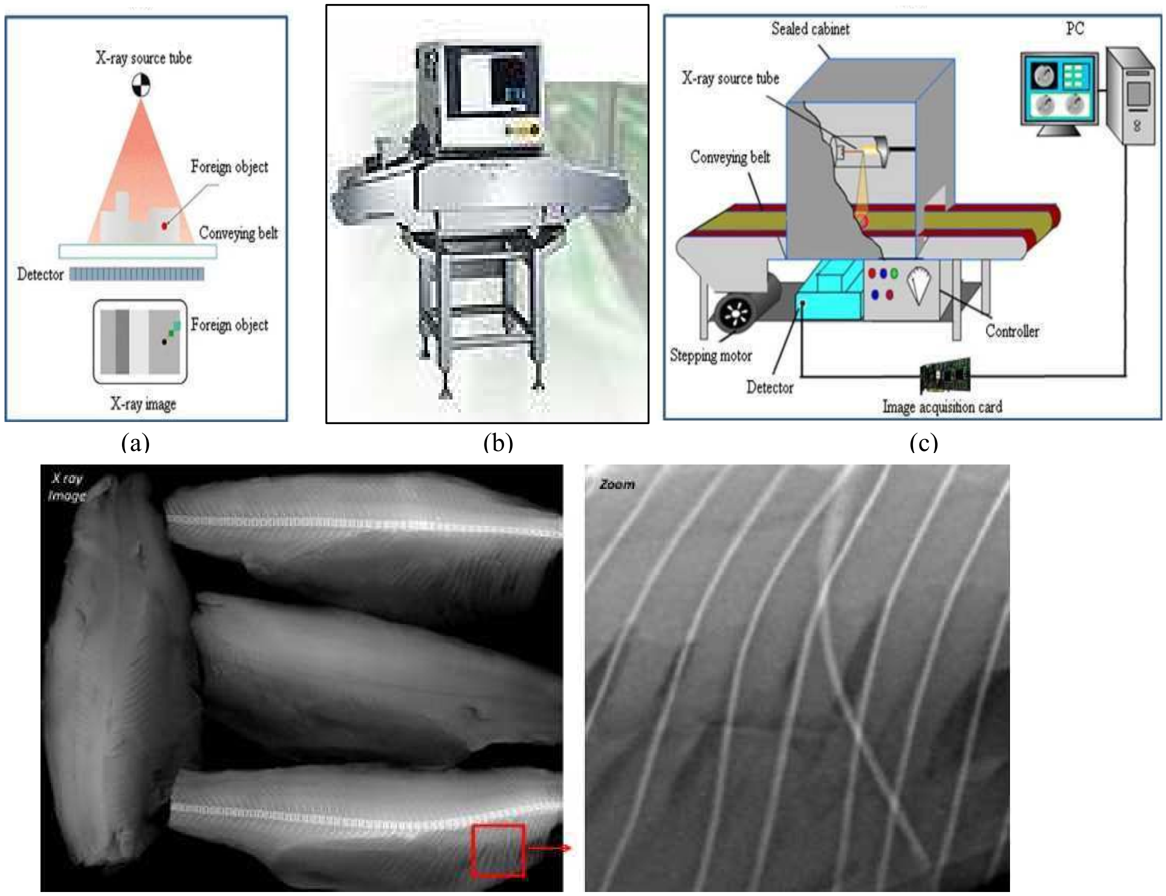
Fig. 9.



(a) (b) (c)

(d)

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Fig. 10.

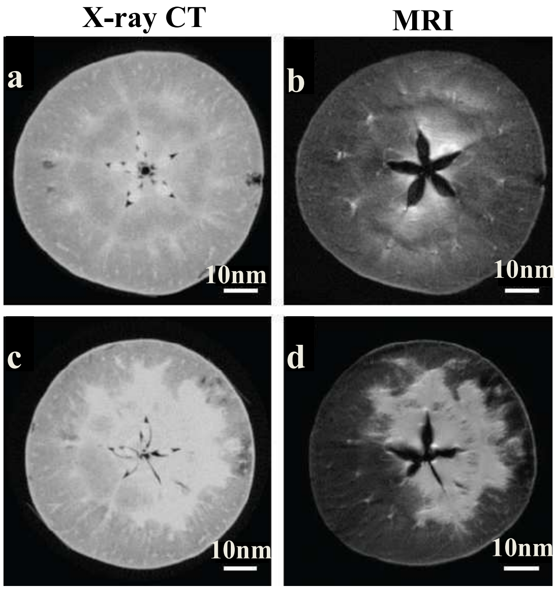

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Fig. 11.

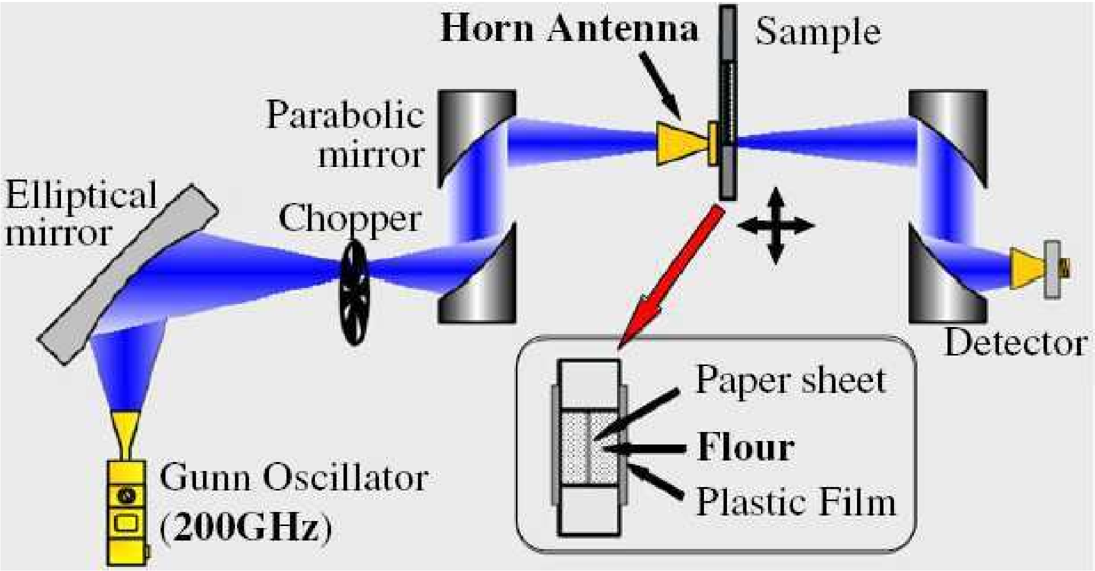

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Fig. 12.

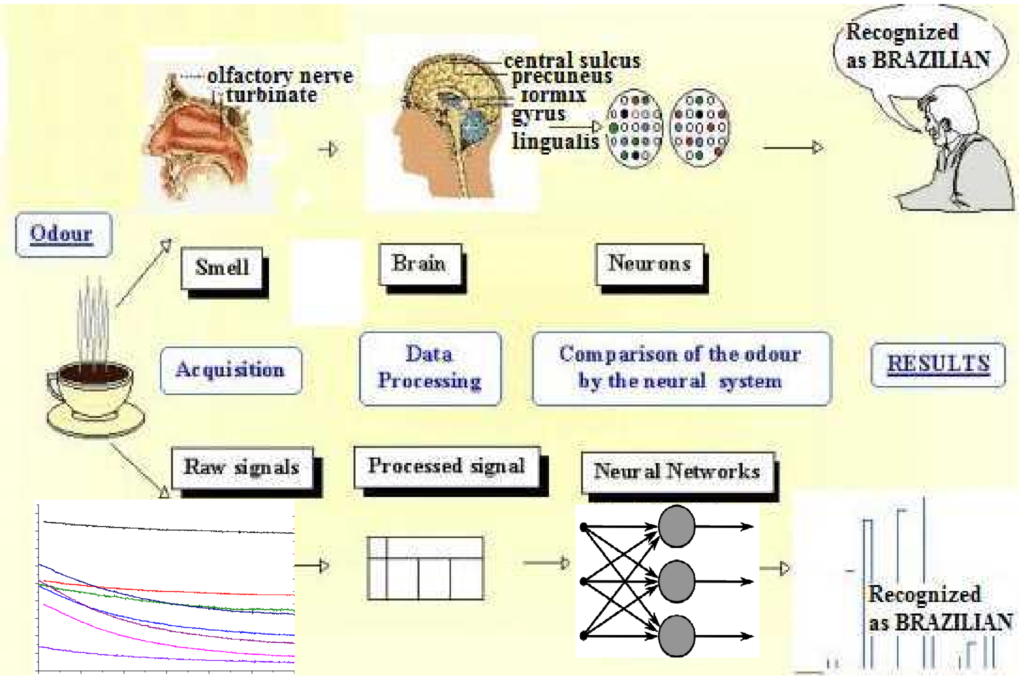

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Fig. 13.

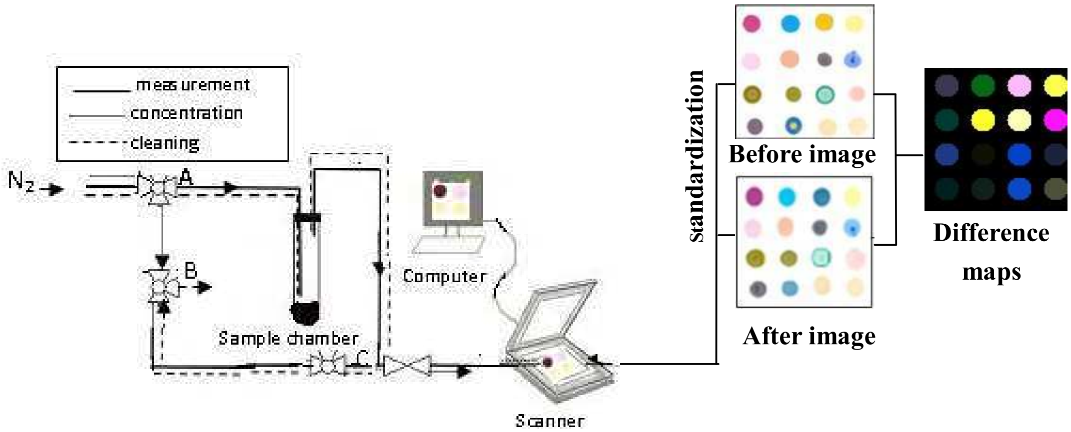
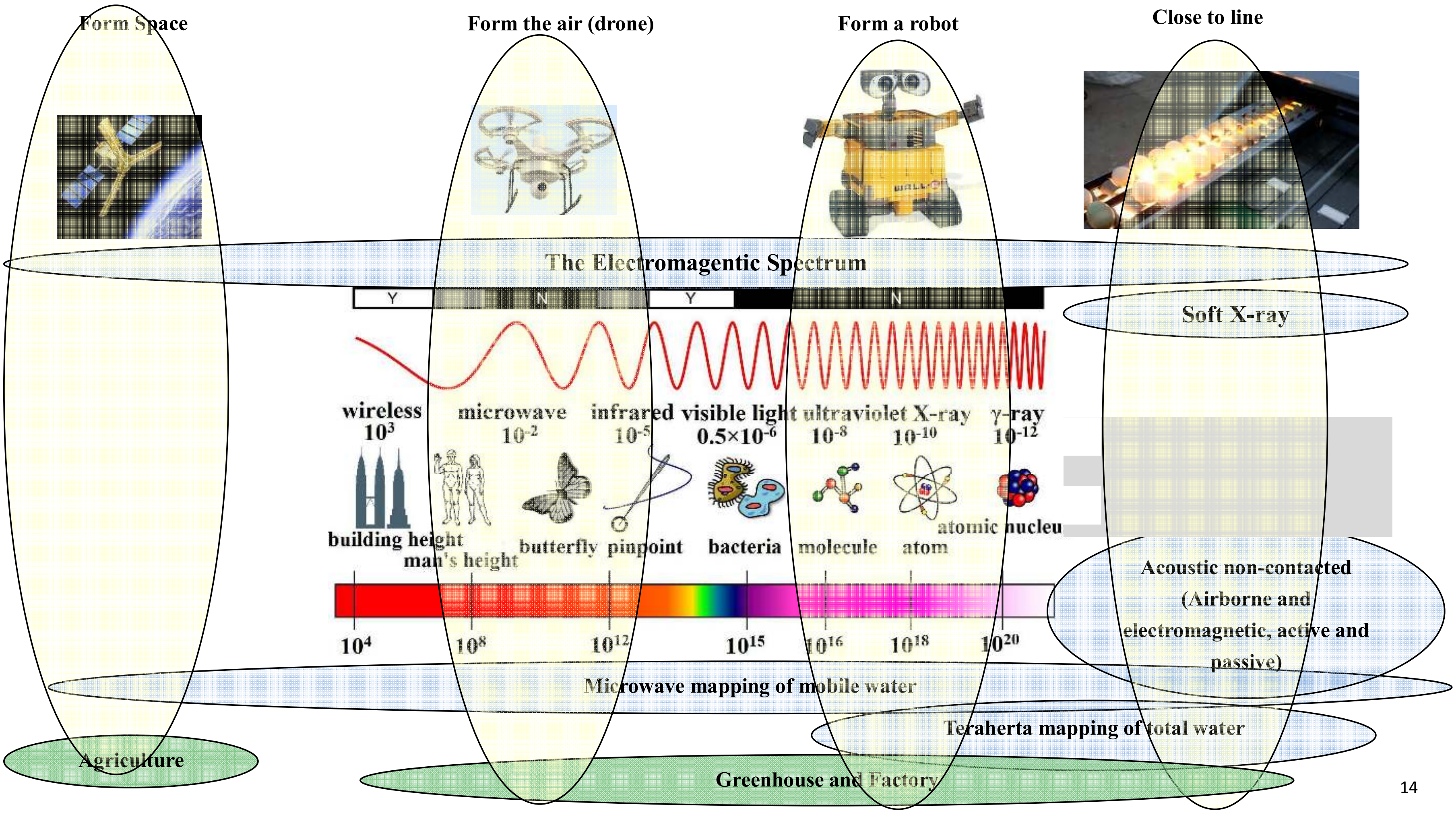


Fig. 14.


Form Space
Form the air (drone)
Form a robot
Close to line
WALL-E
The Electromagentic Spectrum
Y
N
Y
N
Soft X-ray
wireless 10^3
microwave 10^{-2}
infrared 10^{-5}
visible light 0.5×10^{-6}
ultraviolet 10^{-8}
X-ray 10^{-10}
γ-ray 10^{-12}
building height
man's height
butterfly
pinpoint
bacteria
molecule
atom
atomic nucleu
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Acoustic non-contacted (Airborne and electromagnetic, active and passive)
Microwave mapping of mobile water
Teraherta mapping of total water
Agriculture
Greenhouse and Factory