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Review

A Review on the Commonly Used Methods for Analysis of Physical Properties of Food Materials

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Abstract: The chemical composition of any food material can be analyzed well by employing various analytical techniques. The physical properties of food are no less important than chemical composition as results obtained from authentic measurement data are able to provide detailed information about the food. Several techniques have been used for years for this purpose but most of them are destructive in nature. The aim of this present study is to identify the emerging techniques that have been used by different researchers for the analysis of the physical characteristics of food. It is highly recommended to practice novel methods as these are non-destructive, extremely sophisticated, and provide results closer to true quantitative values. The physical properties are classified into different groups based on their characteristics. The concise view of conventional techniques mostly used to analyze food material are documented in this work.

Keywords: food industry; food physics; quality control; physical methods

1. Introduction

The physical properties of food materials have defined those properties that can only be measured by physical means rather than chemical means [1,2]. Food materials are basically naturally occurring biological-originated raw materials that have their own exclusive physical identity that makes them unique in nature [3]. Due to the uniqueness of their physical properties, to properly measure the different physical characteristics of any food materials to get control and understand about the changes in their native physical characteristics with the influence of time-temperature-processing-treatment-exposure, proper measurement techniques for various physical properties of food materials are required with numerous desired outputs [4]. Since the inception of mechanization in measurements, various approaches were introduced by various scientists aiming at different desired outputs with different application purposes. In the case of food materials, proper measurements of different physical attributes are very much important for new product design and development, shelf-life enhancing and, most importantly, to maintain food safety and quality parameters [5–7]. Among the different conventional methods, most of the methods are time-consuming, laborious, and destructive, since during measuring operations the food products were either completely destroyed, were wasted, or got contaminated [8]. That means a huge loss results when measuring the physical attributes of a food product and also during processing. The proper measurement of different attributes is not possible, which results in improper measurement with respect to the different processing conditions [9]. Also, conventional measurement techniques are incapable of capturing the real-time changes of the product's physical characteristics with changes in process parameters and also incapable of finding out the complex behavior of the inter-associated and intra-associated critical physical parameters [10,11]. Currently, with the help of emerging digital techniques, various novel techniques for measuring different physical properties of different food products are being introduced in the market along with evolutionary sophisticated high-end instruments with state-of-the-art facilities. Currently, these instruments are capable of capturing and estimating the real-time changes in food's physical properties with almost zero product loss [10,12]. These new-age measurement approaches also provide reliable data and information concerning the physical properties and functional behavior of food components, which is critical and helps the food processors evaluate the possible substitution of food ingredients in new or existing food products. For the proper design of a new food product, we need a huge set of data under a different set of parameters with different operational conditions and this is only possible with the help of emerging novel digitalized measurements techniques [13]. Therefore, data generation is one of the prime driving factors behind the demand for measurement techniques involving novel methods [14]. There are several books [15–18] and review works [19–21] available about techniques for the analysis of the chemical and physical properties of food materials, but only a limited number of studies on the commonly used analysis techniques, their principles, applications, advantages, and disadvantages. In this review, the contemporary methodologies for estimating the physical properties of food materials are covered, aiming at a complete study of measurements of food materials.

2. Importance of Physical Analysis Methods in the Food Industry

Physical testing in the food industry refers to the methods used to evaluate a food product's varied physical qualities. Color, viscosity, weight, thickness, granulation size, and texture are all common food product attributes examined. Physical testing in the food industry is usually employed as a quality indication, but it can also be used to ensure product consistency. Manufacturers can utilise this to evaluate product value, connect a product to consumer perception, and, in some situations, ensure food safety when a product must be cooked. Unusual physical outcomes could indicate a problem with the shelf life, production, and supply chain. Physical testing has a distinct advantage for businesses in terms of monitoring their suppliers' items and catching problems before customers complain. Furthermore, when physical qualities are assessed in conjunction with consumer research, the physical test specification ranges can be linked to desirable product information. This can help determine preferences in terms of appearance, such as a certain hue, or texture, such as viscosity, firmness, and consistency. Because a product's physical properties impact customer perspective and acceptability, determining optimal physicochemical characteristics can aid product development teams and retailers with knowledge on the part for drawing conclusions. Technologies that help in the physical analysis of food material is a subject of growing interest because of their non-destructive nature (Figure 1). Since the last half of the 20th century there has been an increase in the search for new physical analysis methods for the food industry. In Scopus and the Web of Science, a moderate number of papers are being published on this topic, and most of the published articles are research articles. The published works available in the field basically describe the working procedures, results, and validation of some particular methods on specific food products. Keyword searching reveals that the techniques to analyze the physical property of food materials are gaining the interest of researchers from academia, as well as from industry (>25 in 2022 to date, >75 in 2021 and >50 in 2020). Bibliometric analysis has revealed that there are several research papers available on the techniques for analysis of various physical properties of food materials, but there is a need for a concise review of the principles, specific field of applications, merits, and demerits of the techniques to provide an overall view of the rigorously practiced methods.

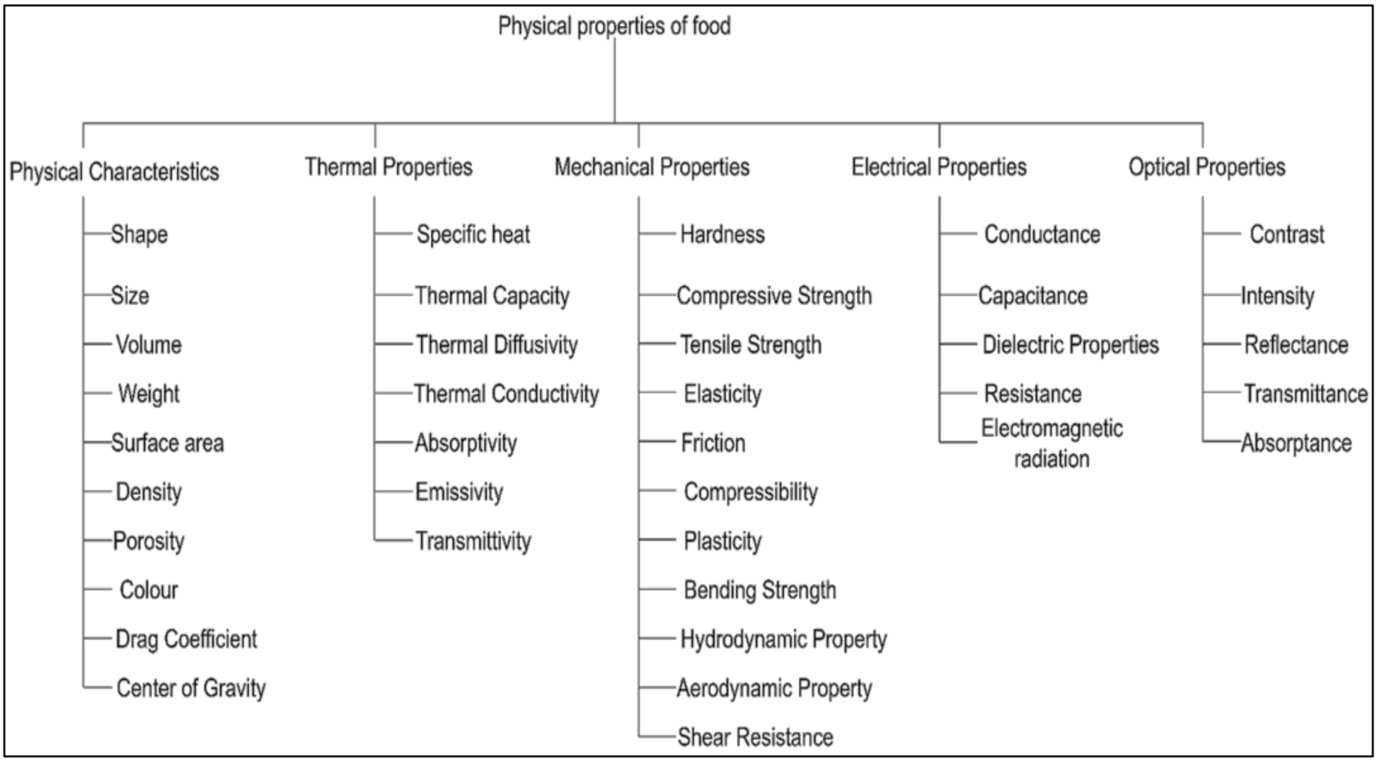

Figure 1. Classification of physical properties of food materials.

3. Techniques for Non-Destructive Physical Methods

During recent years, researchers have applied several novel techniques in the field of physical property assessment of different food commodities. Depending on the physical states of the food material, the methods of physical techniques that have been employed are described in Figure 2.

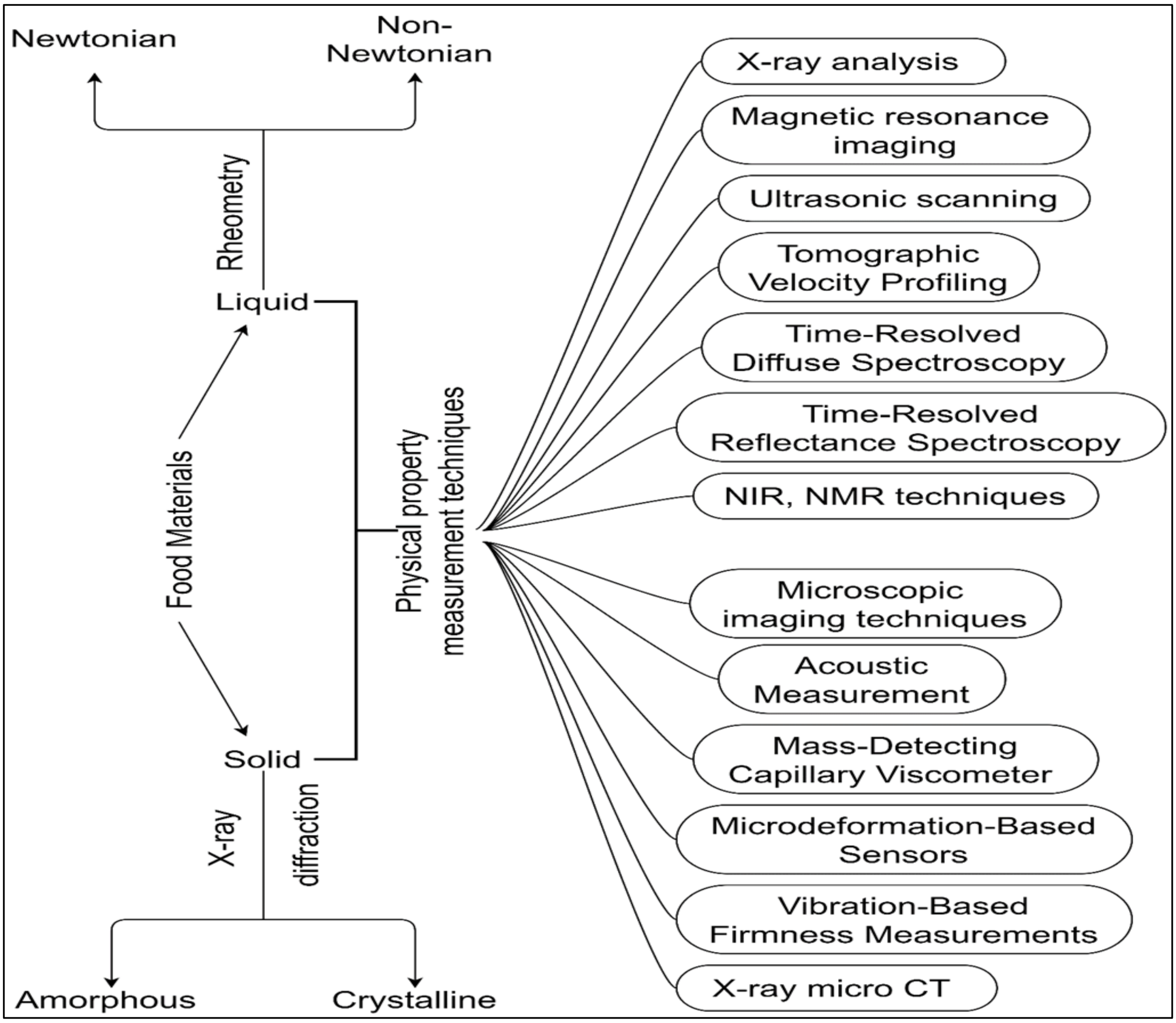

Figure 2. Novel techniques for assessment of physical properties of food materials.

3.1. Ultrasonic Wave-Based Analysis

The ultrasonic frequency is beyond audible to human hearing. These acoustical or mechanical waves have a frequency of $\geq$20 kHz. An ultrasonic scanning system can be used for food diagnostic purposes (physicochemical properties like flow rate, structure, composition, and physical state), especially for soybean, honey, cereals, meat, and aerated foods (Table 1) [22]. Volume estimation, firmness, maturity of fruits [23–25], rheological properties of cereal products [26], determination of fat percentage in meat [27], and defect detection in cheese [28] have been measured or conducted with ultrasound. Ultrasound velocity, attenuation coefficient, signal and wave amplitude, acoustic impedance, and relative delay are the parameters considered for analysis of food materials [29,30]. The techniques provide the following advantages: portable, simple, low power consumption, lower operational cost, adaptability for both liquid and solid foods, and environmentally friendly [29]. The limitations of the techniques are shock wave generation, followed by degradation of products, and radical formation followed by off-flavor formation in the products subject to analysis. Surface characteristics and homogeneity of products may affect test efficiency and the development of mass transfer resistance [22].

3.2. Young's Modulus and Poisson's Ratio

The Sitkey technique was applied by researchers to determine the Poisson's ratio as a function of moisture content and Young's modulus as a function of loading rate. A material testing machine was used to perform the test. It found that there is a negative correlation between the Poisson's ratio of the grains and moisture content. On the other hand, the reverse was found for the loading rate. For the grains, Young's modulus is inversely proportional to moisture content and loading rate [31].

3.3. Compressibility Analysis through High-Pressure Processing (HPP)

Processing food by applying high pressure is now an impactful technique to preserve different foods. High pressures exhibit bulk compression loading on the food. At high pressure (400–1000 MPa) and adiabatic conditions with a pressure change of 100 MPa, there is a change in water temperature of 3 °C. Pressurization of food material leads to changes in rheological properties, thermodynamic properties, and compression heating [32]. It is a non-destructive green technique, but the food composition and solute concentration are the limiting factors for the efficacy of the technique. Moreover, it is not suitable for solid food products [32].

4. Techniques for Mechanical Impact Assessment

Non-periodic, non-continuous, and instantaneous load is defined as a mechanical impact. If two convex bodies are in contact and one of the bodies has a high velocity, there may be different effects, such as wave propagation and contact in the impact area [33].

4.1. Hertz Contact and Impact Measurement Parameters

Food samples show that there can be three categories of impact measurement parameters. These parameters can be listed as absorbed energy, load velocity, impact energy, and rebound energy. All of them are categorized into three groups: (i) maximum impulse, bruise dimensions, permanent and maximum deformation, and critical deep; (ii) rebound velocity, the slope of the force-time curve (S), maximum impact force (F), and the ratio of F and S; and (iii) impact duration (ID), time of impact (TI), TI–ID, etc. [34,35]. These parameters possess a linear correlation with the ripeness stage of the fruit [35]. The use of this correlation quality and these maturity indexes for fruits can be developed with the help of parameters. Researchers have proven that the elasticity modulus of fruits is correlated to their maturity stages and have classified the fruits based on the ripening stage [36,37]. In this technique, it has been assumed that the contact area is circular and frictionless, and that deformation should be within the limit of deformation. Thus, the technique is suitable only for good quality, sphere-shaped, and smooth-surfaced fruits. But the method is useful for collision mechanic models [35].

4.2. Vibration Study and Mechanical Impact Based Method

The study of vibrational characteristics leads to the determination of fruit firmness using an elasticity modulus. From different studies, it can be concluded that waves transmitted through the fruit surface with velocity transmission provide highlights of fruit texture attributes such as firmness, as the ripening condition of fruits is correlated to velocity of wave propagation [38]. An advantageous feature of the technique is that it supports condition monitoring from a distance. For predictive maintenance, well-established signal assessment methods are available, supported by a variety of commercially accessible sensors for diverse operational scenarios. Meanwhile, the demerits are as follows: it is difficult to pinpoint the source of a problem; fracture development is hard to track; and there are a lot of prerequisites for the development of a good system architecture [39].

5. Techniques for Texture Profile Analysis (TPA)

To correlate the rheological property of food with the mechanical testing method is a great challenge. Instron universal testing machines (UTM) are successfully employed to understand food rheology. TPA is an instrumental method that compresses the testing material for two times the mechanical parameters that are quantified from the force deformation curve (Table 2) [40,41]. Figure 3 represents the physical properties of fruits and vegetables and their techniques for measurement.

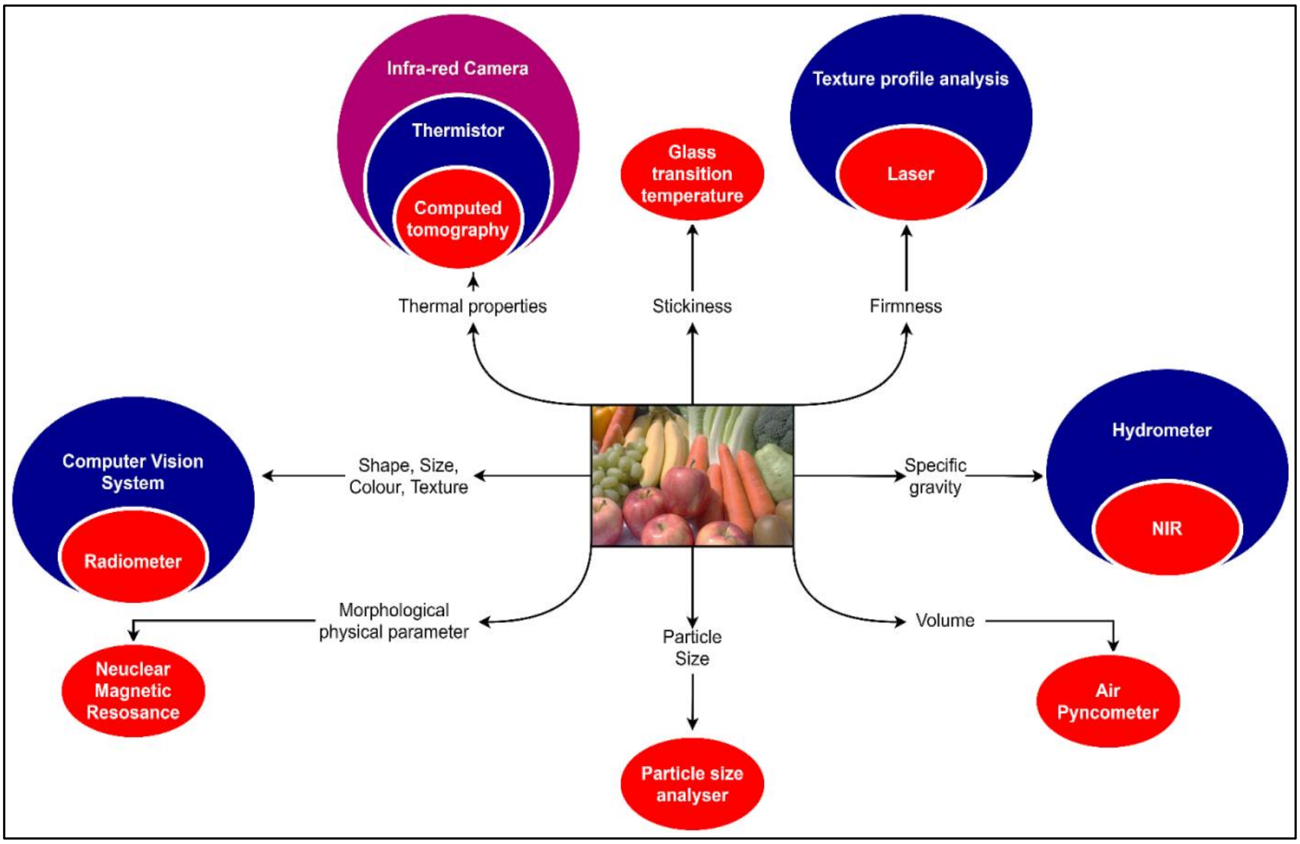

Figure 3. Physical properties of fruits and vegetables and their techniques for measurement.

TPA Performance

Several studies have proved the need for TPA. The effect of reduction in fat content on cheddar cheese texture has been observed by researchers. It has been found that the rheological properties like hardness, adhesiveness, springiness, and values from the instrumental analysis are extremely correlated with the sensory analysis [42]. Researchers have observed that composition and storage facilities significantly affect the resilience, chewiness, and firmness of sliced cheese [43]. Near-infrared hyperspectral imaging is one of the non-invasive techniques for TPA measurement. Researchers have successfully implemented the technique for salmon fillets [40]. Biospeckle activity is another novel optical technique for firmness analysis that has been implemented to ascertain apple firmness [44]. The TPA performance depends on the sample height, compression speed, diameter ratio of sample and probe, initial height over the sample, and geometry of the probe used [45]. Despite the numerous published publications on the use of instrumental TPA to define solid foods, it cannot be considered a unified method. This is because the instrumental TPA, in all of its forms, has a number of fundamental defects (e.g., calibration-related issues, mechanical issues) [46]. The sample height is important in determining the TPA. Similarly, friction between sample and plates, overall dimension of sample and aspect ratio may affect the analysis results. However, it is obvious that bite size is not the determining factor for the texture in real cases [46], although the simplicity of the approach and its cost-intensive nature make it a popular method in food texture analysis.

6. Novel Techniques for Viscosity Analysis

6.1. Tomographic Velocity Profiling

Tomographic velocity profiling is one of the emerging technologies. The working principle lie in the measurement of the velocity profile, which is specific to a cross-section of pipe and thereby determines the drop in pressure for a specific length. Unlike regular tube viscometry, whose theory is based on volumetric formulas for measuring viscosity data points, tomographic viscometry involves shear rate data points from the viscosity profile [47,48]. The non-invasive and non-destructive manner of operation, as well as the in-line measurement of rheological parameters (e.g., slip velocity, yield stress, and shear viscosity) are the advantageous features of the process. In most liquid food, scattering particles are present that determine the flow characteristics. For food materials where scattering particles are more abundant, a portion of the velocity profile may be recorded instead of profiling the entire velocity [49].

6.2. Mass-Detecting Capillary Viscometer (MDCV)

The MDCV has been used to study the rheology of dairy products for a shear rate range measuring the variation of liquid-mass with time. The operation process is simple and easy. A wide range of shear rate (1–10^3/s) can be measured for non-Newtonian fluids [50]. The MDCV is capable of measuring the continuous change in viscosity over a range of shear rate through the measurement of alteration in the mass of liquid with respect to time.

6.3. Ultrasonic Doppler Velocimetry (UDV)

Viscosity is an important physical parameter of food. UDV can be effectively employed for viscosity determination. In the industrial scale crystallization process, UDV is employed. Flow behavior, complex rheological behavior such as yield stress, and viscoelasticity can also be measured [51]. The non-intrusive design of UDV is advantageous, apart from that it has other merits like ease of installation, lower contamination chance, lower chance of leakage, insensitivity toward density, viscosity, and temperature of fluid, and the potential to work with corrosive liquid. But operating UDV is difficult for fluids with very low velocity. To reflect the ultrasonic signal, the liquid stream must contain any kind of particles and/or bubbles and, therefore, UDV is not suitable for highly clean fluids or water. The particle distribution within the fluid may affect the performance of the UDV [51].

6.4. Reflectance Sensor

A reflectance sensor acts on the principle of reflectance at the liquid surface as it does not transmit through the liquid. Evaluation of the viscosity of the food products is done with the help of density and viscosity sensors. This method is gaining increased popularity because of its robustness and also because flow rate and vibrations have no impact on the process [52]. Upon reflection on the surface of the liquid, the shear wave propagates approximately one-half of a wavelength (i.e., ~1 mm) within the sample, thus near-surface characteristics should be the indicative of the bulk, or otherwise useful information cannot be generated. Frequencies at which commercial shear transducers operate are substantially quicker than most real-world fluid deformations [53].

6.5. Ultrasonic Wave Propagation-Based Sensors

Food materials are susceptible to the different processing techniques applied to them. That is why minimal processing with low-density ultrasonics are non-destructive. Textural analysis can be done by measuring velocity and attenuation. If tissue analysis of whole fruit is required, then a single-touch system may be used for whole fruit [30]. Continuous and on-line analysis is possible with this technique. Sensors may malfunction in extreme alterations in temperature and radical convection. The other drawbacks for the technique are inflexibility in the methods of scanning and limitations in testing distances [54].

7. Emerging Techniques of Measurement of Firmness

The firmness of food products is a reflection of the quality of food. It is one of the attributes upon which consumer acceptance is decided. Available tests are generally destructive tests that are not applicable to firmness-based grading [55].

7.1. Non-Destructive Impact-Based Measurements

Fruit impact with sensing elements and dropping the fruit on force transducers are the two methods for impact measurement. Several studies have shown the use of the non-destructive detectors or sensors for impact analysis [56].

7.2. Non-Destructive Microdeformation-Based Sensors

Deformations may occur in fruits during compression. To mitigate this issue, non-destructive sensors are used that can measure the extent of deformation during compression. A spherical plunger is used for indenting the fruit surface, taking care of the damage issue [57,58]. A piezoelectric sensor or analogue record the non-destructive force-deformation curve that is positioned at the back of the compression plunger [59]. The maximum pressure and slope of the plunger are the limiting factors for this technique [60].

7.3. Vibration-Based Technique

This technique involves the fruit being subject to blows from a small hammer. The produced mechanical vibration is estimated with the help of accelerometers or laser vibrometers. The computer system is attached to a measuring instrument to calculate the frequency response spectrum obtained from the time domain signal. The resonance frequencies are directly related to the mechanical properties of the fruit. Hence, fruit firmness can be characterized from these data. The resonance frequency and fruit firmness are directly proportional [61]. The demerit of an accelerometer-aided technique is that in this technique the device needs to be attached to the fruit surface, which may cause surface patches. Apart from this, concentration of excitation energy and un-uniformity are the other drawbacks of this technique, while the laser vibrometer technique can measure the real-time vibrational signal without surface contact with the food [62,63].

7.4. Image-Analysis-Based Methods

The first criteria to attract consumers to fruits are probably texture and appearance. A machine vision system may be applied for judging fruit characteristics. Light scattering is a reflection of the structural characteristics of the fruit. Hence, it can be used to judge fruit firmness. The optical system method is successfully employed to determine apple fruit firmness. A 670 nm laser was used for light scattering. The camera and stereomicroscope were set up for measuring their scattering. The region of interest can be selected according to the studies targeted using hyperspectral imaging (HI) to accommodate the drawbacks of juncture assessment and/or background noise. Both spectral and spatial information can be gathered with this process [64]. Smartphone-based digital image analysis is an emerging section in food quality analysis [65]. The image-analysis-based methods are suitable for non-invasive analysis of meat, fish, and poultry products (Figure 4). The non-destructive and non-invasive characteristics, in-line adaptability, and little or no sample preparations are the features that make the technique popular. However, the complexity, cost involvement, and sensitive detectors are the limitations for HI. While the requirement of a large database, computational complexity, and the requirements for large storage space and fast computers are the limiting factors for digital image analysis.

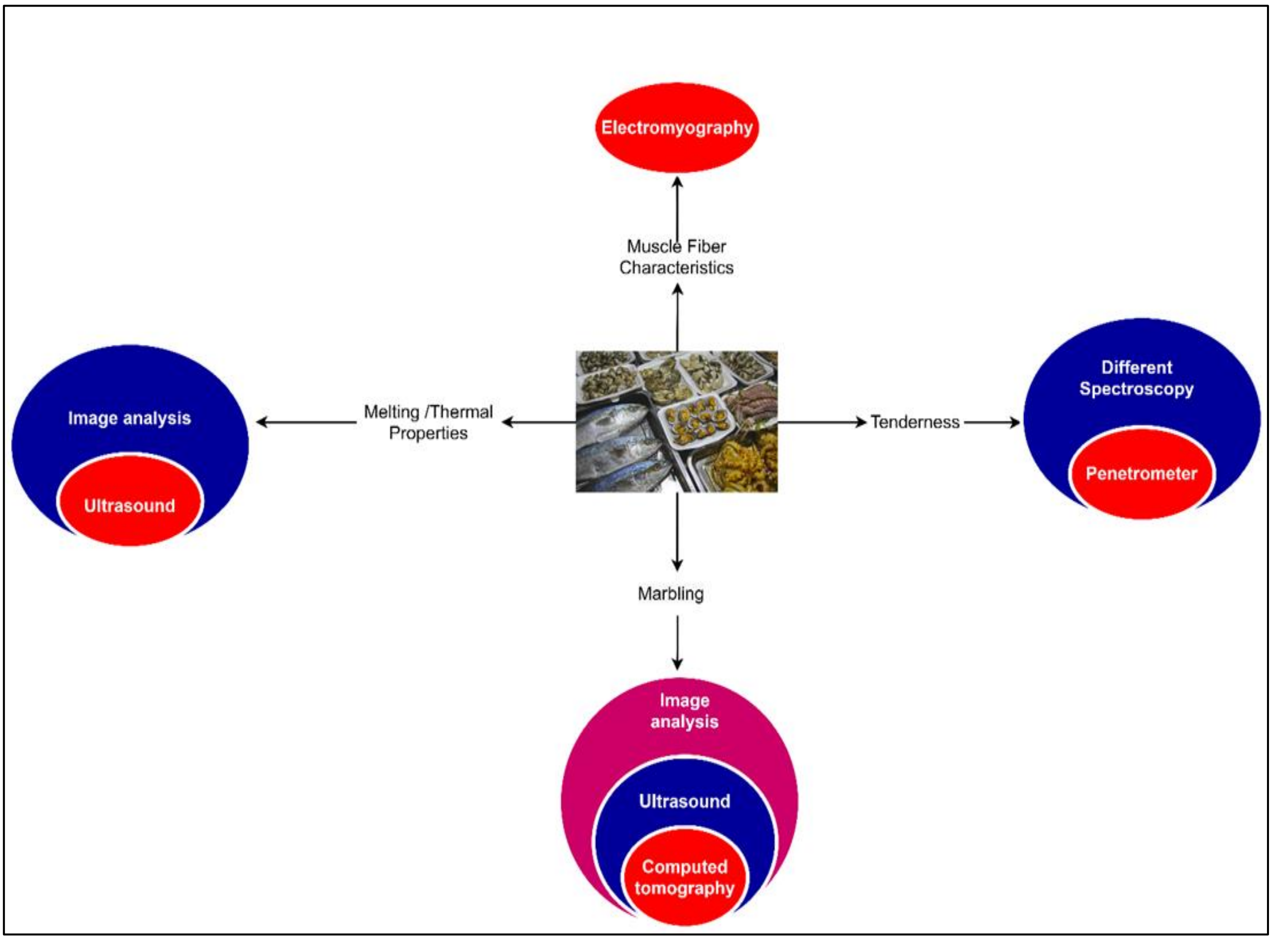

Figure 4. Physical properties of meat, fish, and poultry products and their techniques for measurement.

7.5. Near-Infrared Spectroscopy (NIR)

In NIR, the electromagnetic range is set between 780 nm and 2500 nm. The incident radiation on the food sample is measured with a spectrophotometer. Radiation on the sample may be absorbed, reflected, or transmitted, and therefore each phenomenon reflects food characteristics. From absorption data, the chemical composition of the sample can be measured. Meanwhile, the microstructure of tissue can be related to scattering [66]. It is a non-invasive, rapid method and no or very little sample preparation is required for this technique [67]. Overlapping and the presence of multiple peaks are abundant in NIR spectra. Thus, multivariate analyses coupled with statistical analysis are required to extract the significant information [68].

7.6. Ultrasonic Wave Propagation Methods

It is the non-destructive method that assists in the determination of the freshness of food materials. A pair of ultrasonic transducers (80 kHz) is used to determine the mealiness in food. One of the transducers transmits a pulse through food tissue and thereby, based on the internal texture of the food, the tissue absorbs energy. Another transducer gets the transmitted pulse as an emerging signal [30]. Peak frequency, attenuation, and the flight and wave velocity of transmitted signals are analyzed to determine the firmness characteristics, such as elastic modulus and bioyield strength. For peach (0.542), pear (0.730), and apple (0.792) strong correlation coefficients have been observed for the prediction model of bioyield strength [69]. The requirement of a relatively smooth surface and complications for food materials with irregular shapes (e.g., jackfruit) are the limitations of this method.

7.7. Time-Resolved Diffuse Spectroscopy (TRS)

To characterize highly diffusive media, the TRS method can be employed. A laser light pulse is used in TRS, and it is injected into the sample under study. Here, the absorption coefficient is represented by μa, and μ is the transport scattering coefficient. These two can be evaluated from the time distribution curve [70]. High temporal and spectral resolution is obtained in this non-destructive technique. The absorption characteristics are representative of the bulk material and not a characteristic of surface attributes. The absorption coefficients and transport scattering coefficients are under 1 cm^{-1} and 25 cm^{-1}, respectively, for fruits with thin skin [71]. Thus, it is not suitable for thick-skinned fruits.

7.8. Nuclear Magnetic Resonance (NMR) Spectroscopy and Magnetic Resonance Imaging (MRI)

The NMR technique has served as a novel method for food analysis for many years. It can easily detect the presence of sugar, water, and oil in food particles. The sensory quality of potatoes has been studied using NMR imaging [72]. The MRI images can be used for firmness analysis predictions with ANN [73]. Researchers have considered MRI and NMR for orange firmness analysis, and built a robust model with 0.84 and 0.92 Pearson correlation coefficients [74]. It is a non-invasive method and can be used for real-time, in-line inspection of food quality. The cost-intensive nature, safety concerns, and requirement for skilled operators restrict the use of these techniques in developing countries [75].

8. Techniques for Crispness Measurement

The quality of dry food may be measured by several attributes, one of which is crispness, but defining crispness for all food commodities is difficult as it may differ from one product to another. Crispness of fruits and vegetables may be defined as the cracking sound that evolved from sudden fracture upon the application of force [76–78]. Besides sensory analysis, there are instrumental methods also available for crispness measurement.

8.1. Mechanical Measurement of Crispness

Mechanical tests applied to crispness measurement may be categorized as compression, shear, and flexure test. The sensory and Instron tests have been used to measure the crispness level of different foods. To conduct the test, various cutting devices are employed and it has been found that, in cereals, shear force may be the crispness indicator [79–82]. The method is simple and rapid, and the output results are easy to interpret and, moreover, are convenient in an industry environment and economically viable [83]. Because of unusual shapes, sizes, and/or the simultaneous presence of non-crisp portions in food, crispness analysis is found to be difficult with this method. Humidification of crisp products causes negative correlations between force and crispness value [84].

8.2. Acoustic Measurement of Crispness

This method is based on the cracking or rupturing sound created during the fracture of the food material [85]. The sound is developed during machine crushing and recorded. Crispness has been measured using sound signal features, and the result was cross-checked by the sensory panelist. An audio recording system is employed with the features: a dynamic microphone, Waver Studio software, and sound card. A neural network technique and principal component regression were used to analyze sound features to predict the crispness [80].

8.3. Ultrasonic Measurement of Crispness

The ultrasonic pulse-echo technique has been used to study the crispness of biscuits [86], ciabatta crust [87], chicken nuggets [88], cornflakes [89], and apples [90,91]. It has been found that the velocity of longitudinal sound and sensory crispness has a strong correlation [76]. It is a non-destructive and rapid method. The key challenge for this technique is to standardize the numbers of the acoustic peak, force peak, and sound pressure level, as these parameters may vary for individual products [92].

9. Woolliness and Mealiness Measurement

Mealiness and wooliness in fruits are such characteristics that are absolutely not acceptable. Mealiness is a state in fruits when sandy texture is observed because of a lack of juiciness [93]. Woolliness is described as a dry, soft texture of fruit with a loss of aroma and flavor. As these attributes of fruits are not easily detectable in the selection chain, non-destructive instruments may be an alternative option. The best possible mechanical test to detect apple mealiness may be the shear stress rupture test. Non-destructive measurement has become more popular these days. These include impact response, ultrasonic wave propagation, NMR spectroscopy, time-resolved reflectance spectroscopy, imaging, and chlorophyll fluorescence.

9.1. Impact Response-Based Techniques

To detect mealy fruits based on sensory analysis, healthy or mealy fruits are classified. We observed that mealiness is highly correlated with maximum resistance to impacts. From the results of the impact-response test, it is easy to classify healthy and mealy fruits. In other experiments, signal detection tools are used, specifically receiver operate curves (ROCs), to get the nature of discriminate analysis with varying cut-off points [94]. Researchers have found that peak accelerometer output and firmness possess lower correlation coefficients for apple (0.55), while the same for pear (0.80) and peach (0.92) are relatively better [95]. The impact location and angle greatly influence the impact response, and therefore the characteristics of the fruit surface may affect the final result [95,96].

9.2. Detection Method Based on Quantity of Free Juice

Mealiness and woolliness are attributes that are defined by a lack of juiciness. The confined compression test has been done with peach and apple. The texture analyzer inserts the load cylinder until the fruit pulp gets maximum deformation. After compression, the fruit juice is extracted and taken in a drying paper. The juiciness is measured as the area stained by the juice. That will in turn correlate to mealiness and woolliness [97]. The process is simple and easy to implement, but the expert opinion is that dependency is the main challenge for this technique [98].

9.3. Techniques Based on Imaging

Images developed from a light microscope may be useful for differentiating between fresh and mealy fruits. Parameters such as area and perimeter (cell parameter), and two roundness parameters are set for evaluation from the images. When the tensile loading test was performed for mealy fruit, fewer broken cells were found in the surface after fracture than for fresh fruit [99]. Multiconstituent information can be accessed with non-destructive techniques, but time- and cost-intensive methods, maintenance of the equipment, and operator skill are other limiting factors [93].

9.4. Time-Resolved Reflectance Spectroscopy (TRS)

Mealiness in fruits was evaluated by time-resolved laser spectroscopy [100]. A confined compression test was done to categorize mealy and non-mealy fruits. The coefficients (optical) were set as variables that will produce functions of identification for mealiness. A calibration curve is prepared with 15 TRS variables. This curve will classify the two types of fruits. It is a non-destructive analysis technique, although the dependency on expert opinion is the major disadvantage [93,101]. The absorption coefficient varies for different fruits, and therefore it is difficult to standardize the absorption coefficients for each type of fruit and for the physical property intended to be measured and subjected to experimentation [101].

9.5. The Use of Modeling for Predicting Mealiness

Fruit mealiness is evaluated with linear regression models [93]. During storage, the level of mealiness was studied by the mechanistic model from the turgor pressure of the tissue. The technique is simple and easy to implement, and a high coefficient of correlation (0.96) has been found. The limitations of the technique are the requirement for an independent data set for model validation, non-consideration of the state variables such as pectin and symplastic water content, and no changes in temperature and oxygen concentration have been assumed [102].

9.6. Methods Based on Chlorophyll Fluorescence

After absorbance of light or electromagnetic waves by any substance, emission at different wavelengths is called fluorescence. Photosynthesis activity is associated with chlorophyll fluorescence measurement. Loss of chlorophyll implies a decrease in the photosynthesis rate, which ultimately shows the ripening of vegetables. A study showed that in the chlorophyll fluorescence kinetics of fruits, with the decrease in fluorescence value, an increase in the mealiness-level fluorescence values was observed. The destructive method showed 82% classification efficiency, while the same for chlorophyll fluorescence was 85% [103]. Based on this result, the mealiness level may be categorized and a more accurate result is obtained than from destructive tests [104]. The method is rapid, non-invasive, and easy to install in packaging lines for quality inspection, although the pigment concentration in the fruit and the temperature dependency are limiting factors [103,105].

10. X-ray Computed Tomography (CT)

Through CT, the interior part of any solid object can be visualized. It is also a non-destructive method. Digital information on the properties of the object can be generated through it. X-ray tubes are mainly used as the source, but gamma rays can also be used [106]. The soxhlet method was compared by researchers to validate the efficacy of CT for fat determination in beef, and satisfactory results ($r = 0.92$–0.99, $p < 0.001$) were observed [107]. Determination of the 3D structure in a non-invasive approach and analysis of pore size, bubble distribution, wall thickness measurement, and the existence of foreign matter is possible with CT, although the cost- and time-intensive nature, operator dependency, and image artefacts (phase-contrast, cone-beam, and beam-hardening) are the limitations of CT [108].

11. MRI Technique

MRI is the formation of a very weak magnetization field produced by atomic nuclei of body tissue in the presence of another magnetic field. The density of the nuclei is correlated to the magnetization, and hence it shows the nature of the distribution of atoms. In an MRI, mainly hydrogen atoms are observed. Therefore, softer tissue with large water molecules can be studied well in an MRI [109]. Fat content (40 ± 23 mg/g) determined by an MRI demonstrated an association with GC (39 ± 16 mg/g) in starving fish. For well-fed fish, however, there was no agreement. This could be attributable to non-triglyceride lipid synthesis in well-fed fish and MRI and GC sensitivity differences. From this study, it is obvious that the MRI may more precisely depict fat content [110]. The non-invasive and non-destructive features of this technique make it attractive for food analysis [73], but for the cost-intensive nature and difficulty in analysis of food materials in the metastable physical state (e.g., subcool materials) [111].

The physical properties, their significance in the food industry, their techniques for measurement, interpretation of the measured results, brief working principle, and the objective of the analysis have been listed in Table 1.

Table 1. Physical properties of different food commodities.

Physical Property	Significance in Food Industry	Unit	Interpretation of Measured Data	Measurement Technique	Principle	Measured Property	Objective of Analysis	Reference
Water Activity (WA)	Assessment of internal structure of the food, effect on food texture and shelf-life assessment.	-	WA > 0.90 growth of bacteria; WA < 0.70 growth of molds inhibit; WA < 0.60 growth of most of the microorganisms inhibit	Water activity meter.	Ratio of the vapour pressure (VP) of the water in food and the VP of the pure water.	Equillibrium relative humidity	Quality characteristic measurement for Sugar and sugar replacers, Starch powders, Agar gels.	[1,112]
Hygroscopicity	Assessment of a food's ability to absorb moisture.	-	Powdered food with high hygroscopicity likely to be clump formation with simultaneous increase in texture hardening	Hygrometers	Works on the concept of evaporative cooling.	Amount of moisture uptake by a specific fod material	Moisture sorption isotherm modeling for starch and wheat gluten, Corn starch, pepper	[113]
Mass	Measure for inertia and heaviness of a body.	kg/g/mg	-	Weighing balance.	A counteracting force is created to be compared to the unknown mass.	Quantity of matter	To meet product formulation standards and manufacturing specifications	[1]
Density	Mass per unit volume.	kg/m^3	>1 kg/m^3 (at STP) food material will sink in water	Hydrometer	Displacement of its own weight within a fluid.	Mass and volume	Alcohol concentration of drinks; Solids in sugar syrups; Density, specific gravity and absorption of fine aggregate; Specific gravity of pigments.	
Specific Gravity	Ratio of the absolute density of a food material to the density of a reference material	-	Determines whether the solid food materials will sink or float in liquid medium	Specific gravity bottle	Liquid densities are measured by measuring the weight difference between an empty and filled bottle and dividing by an equal volume of water.	Density of food materials and water		
Bulk Density	Density of powders like food materials which contain hollow spaces or voids filled with gas, normally air.	g/mL	High bulk density is desirable in terms of food transportation and packaging	-	By measuring the volume of a known mass of powder sample that may have been passed through a sieve into a graduated cylinder.		Determination of powdered food characteristics especially for grinding and spray drying process	
Particle Size	Particles with a regular shape are characterized by their linear dimensions (lengths) along their principal axes.	m/cm/mm	Affect the flowability, solubility and reactivity, and the shelf life, processing condition, organoleptic properties and texture of the final product (e.g., sieving considered for >63 micron particles; sedimentation hindered when size < 10 nm)	Particle Size Analyzer	The angle of incidence light scattering is inversely proportional to particle size.	Diameter	Texture and organoleptic characterisation of chocolate, fibres of grain, powdered food, and sizing of protein nano-fibres.	[114–116]

Table 1. *Cont.*

Physical Property	Significance in Food Industry	Unit	Interpretation of Measured Data	Measurement Technique	Principle	Measured Property	Objective of Analysis	Reference
Specific Surface Area (S.A)	Quantification of internal surface area or size of individual particles within a disperse system	m^2/kg or m^2/g	Materials with 500–3000 m^2/g S.A suitable for solute and gas absorption; 200 m^2/g S.A suitable for catalyst	Brunauer-Emmett-Teller (BET) surface area analysis		Surface area	Mass and heat transfer calculation, gas and moisture permiability through packaging materials	[114–116]
Sphericity	Compactness compared with a perfect sphere of same dimension.	-	Sphericity value ≈ 1 (sphere), ≈0.00271 (cube), ≈0.00155 (cylinder)		Ratio of the surface area of an equal-volume sphere to the actual surface area of the particle.	Surface area and volume	Analysis and design of food process equipment	
Sauter Diameter (SD)	Diameter of a hypothetical sphere with the same specific surface as the irregular shaped particle.	m/cm/mm/µm	Coarse particle (SD > 10 mm); fine particle ≈ 1 mm, ultrafine particle < 0.1 mm	Diameter gauge	Ratio of surface area and volume of particle	Surface area and volume	Grinding characteristics measurement for wheat grain and size reduction characterisation	
Uniaxial Stress	It is caused by a force pushing or pulling the body in a direction perpendicular to the surface of the solid body upon which the force is acting.	Pa	-	Strain gauge hole-drilling method	Deformation around the hole	Deformed area	Alginate gel: stress strain behavior and viscoelasticity. Fruit and vegetable puree products: rheological properties. Ketchup: hydrocolloids and flow behaviour. Powders: flow properties, nonflow problems. Wheat flour: rheological properties using farinograph, extensograph, valorigraph, alveograph device.	[117–122]
Young's Modulus	It is the slope of the linear part of the stress-strain curve for a material under tension or compression.	-	Addition fat reduces the young's modulus i.e., the decrease in rigidity. The harder is the food material the higher is the young's modulus	Oscillating rod	Estimated with the help of stress-strain curve.	Alteration in length, and uniaxial stress		
Bulk Modulus	The relative change in the volume of a body produced by a unit compressive or tensile stress acting uniformly over its surface.	Pa		-	The measure of the ability of a substance to withstand changes in volume when under compression on all sides. It is equal to the quotient of the applied pressure divided by the relative deformation.	Pressure and volume		
Shear Modulus	It is the resulting stress When a force is acting parallel to a surface.	Pa	The higher the shear modulus the higher is the rigidity of the food material	-	-	Pressure and strain		

Table 1. *Cont.*

Physical Property	Significance in Food Industry	Unit	Interpretation of Measured Data	Measurement Technique	Principle	Measured Property	Objective of Analysis	Reference
Newtonian Flow	linear relationship between shear stress (SS) and resulting shear rate (SR).	-	Reynolds no (NR) <2000; visosity not change with applied force	Ball viscometer		Elapsed time for the ball to fall under gravity	Flow behaviour of liquid food materials for process design, quality measure and flexible container design	[117–122]
Non-Newtonian Flow	non-linear relationship between SS and SR.	-	NR >2000; visosity change with applied force	Brookfield viscometer		Torque		
Interfacial Surface Tension (IST)	It is the force of attraction between the molecules at the interface of two fluids.	N/m	Emulsion stability increases with the IST	Force tensiometer	Du Noüy ring method; Wilhelmy plate method	Force and length	Foam stability of ice-cream; Physical properties of chocolate	[123]
Permeability	Quantification of the relative ease with which a transporting substance can pass through the material.	m^2/s-Pa	Lower the permeability of the packaging material lower will be the shelf life of the food product	Helium Permeability Meter		Pressure, mass	Undertanding the moisture transfer phenomenon during drying of fruits; mass tranfer phenomenon in lactose crystallization, Whey-protein-coated plastic films; design of pulse electric and ohmic heat process.	[124–127]
Conductivity	It can be defined as a measure of electrical conduction.	Siemens per meter (S/m)	Efficiency of pulsed electric and ohmic heat proces is depend on conductivity of food materials	conductivity meter	It is the ability of a material to conduct electric current.	Resistivity		
Resistance	It is a measure of the opposition to current flow in an electrical circuit.	Ohm (Ω)	Juiciness and tenderness of meat products are correlated with the resistance	Ohmmeter	Deflection of pointer to left or right side in ohmmeter due to current passing through it indicate low/high resistance.			

Table 1. *Cont.*

Physical Property	Significance in Food Industry	Unit	Interpretation of Measured Data	Measurement Technique	Principle	Measured Property	Objective of Analysis	Reference
Heat capacity (HC)	Thermal property that indicates the ability of the material to hold and store heat.	Joule per Kelvin(J/K)	Food materials with high HC have more energy and take higher cooking time	Differential scanning calorimeter	The difference in the amount of heat required to increase the temperature of a sample and reference are measured as a function of temperature.	change in temperature, heat flow/unit time	Characterization and understanding of thermo physical properties for meat; modelling thermal properties for cheddar cheese; prediction of thermal properties during freezing and thawing for meat and dough; thermal conductivity and heat capacity for shrimp; investigation for thermal properties of ice-cream and heat conductivity of food materials	[128–130]
Thermal conductivity	Heat transfer ability of food	Watts per meter-Kelvin (W/(m·K)	It dictates how quickly heat may be evenly distributed throughout the food mass, affecting the quality of the end product.	Thermal conductivity meter (The two types of thermal conductivity meter are steady-state and non-steady-state, also called transient, conductivity meters)	Steady state (when the temperature of the substance being measured remains constant over time), frequency (sensor and hot-wire based method), and time domain (During the heating up phase, transient approaches take measurements) techniques.	Amount of heat transfer, change in temperature, surface area of food material		
Thermal diffusivity (TD)	It is the thermal conductivity divided by density and specific heat capacity at constant pressure.	Square metres per second ($m^2\ s^{-1}$)	Most of the food materials lies within the range of $1.05 \times 10^7\ m^2\ s^{-1}$ (apple juice) to $1.82 \times 10^7\ m^2\ s^{-1}$ (peas). Higher the TD the lower time will require to cool or heat the product	Discovery Flash Diffusivity instruments	-	Density, specific heat capacity, thermal conductivity		
Calorific value (CV)	Heat generated due to complete combustion of specified quantity at constant pressure under normal conditions.	kJ/kg	4 kcal/g for carbohydrate and protein and 9 kcal/g for fat, higher the CV higher is the energy content of the food	Bomb Calorimeter	Energy released by burning a representative sample in a high-pressure oxygen atmosphere within a metal pressure vessel or "bomb" absorbed within the calorimeter and the resulting temperature change within the absorbing medium is noted.	Increase in temperature		
Capacitance	capacity of a component to collect and store energy in the form of an electrical charge.	Farad (F)		capacitance meter	The capacitance meter works based on the directly proportional relationship between capacitance and a time constant.	Voltage	Fish quality measurement using electrical properties and Monitoring microbial growth	[131–133]
Inductance	Ability of an inductor to store energy.	Henry (H)		LCR meter	-	Cross sectional area, length and current		

Table 1. *Cont.*

Physical Property	Significance in Food Industry	Unit	Interpretation of Measured Data	Measurement Technique	Principle	Measured Property	Objective of Analysis	Reference
Paramagnetism	Weakly attachment towards magnetic fields.	-	If the total number of electrons in a molecule is 10 and 16, or odd, the molecule is paramagnetic.	-	-	Electron configuration	On-line water content during cooking for rice; NMR imaging during drying process of noodles; meat muscle characterization, water binding, freezing by NMR for meat	[134]
Diamagnetism	Magnetic property assesment	-	If the total number of electrons in a molecule is even except 10 and 16 the molecule is paramagnetic.	-	Change in the motion of electrons upon application of magnetic field	Electron configuration		
Ferromagnetism	Strong attachment towards magnetic fields.	-		-	-	Electron configuration		
Electric polarization	Separation of centre of positive charge and the centre of negative charge in a material with help of high-electric field.	Coulomb per square metre ($C \cdot m^{-2}$)	It influence the dielectric heating of food materials	Polarimeter	-	Dipole moment	Sequential treatment of drinking water with UV and ozone; combined treatment of pulsed light and to inactivate microorganism;pulsed UV treatment of milk; gelling temperature investigation of gelling gels, rheologic and dielectric properties; analytical fingerprinting with spectroscopic techniques for butter and margarine; identifying coffee arabica, robusta and blends by NIRS.	[135–139]
Refractive index	Ratio of the velocity of light in a vacuum to the velocity of light in a material.	-	Higher refractive index refers to higher total soluble solid content	Refractometer	The concentration of a particular substance within a given solution is measured. It operates based on the principle of refraction. When rays of light pass from one medium into another, they are bent either toward or away from a normal line between the two media.	Angle of refraction	Measure for concentration and purity of food materials	
Colour	Sensory attribute	TCU (True Color Unit)	L = 0 (black), = 100 (white); a = +ve (red) = −ve (green); b = +ve (yellow), = −ve (blue)	Colorimeter	It is based on Beer-Lambert's law, according to which the absorption of light transmitted through the medium is directly proportional to the medium concentration.	Concentration or intensity of colour	standardising and checking of ingredient colour allows them to maintain control over the colour of their final goods and analyse colour changes during manufacturing, transit, and preservation.	

Table 2. Physical methods of analysis for different food commodities.

Food System	Techniques	Key Feature	Quality Attribute	Application	Reference
Fruits and Vegetables	Computer vision system	Non-invasive and rapid method	Shape, size, mass, volume, colour, texture, external damages, calyxes.	Indian gooseberry, Mushroom	[65,140–143]
	Air pycnometer	Boyle- Mariotte law; Time consuming process	Volume	Grape	[144]
	Optical ring sensor	Light-blocking-based system (LBB)	Size	Potato	[145,146]
			Volume	Zucchinis, cucumbers	[147,148]
	Orthonormal imaging	Orthonormal algorithms	Volume	Carrot	[149]
	Imaging	3D surface modeling	Mass and volume	Tomatoes, carrot, apple	[150]
	Volume intersection	Irregular shape determination, cost effective	Volume, surface area	Tomatoes, apples	[151]
	Machine vision system artificial retina, photo sensor	Digital image analysis is not required	Volume	Eggplant, orange	[152]
	Radiometer	Adequate for prolate fruits	Size	Jalapeño	[149]
	Hyperspectral imaging		Weight	Pepper	[153]
	Hydrometer	Cost effective	Specific gravity	Potato	[154]
	NIR spectroscopy	Non-destructive	Specific gravity	Pinus taeda	[155]
	Particle size analyzer	Diffraction angle-based measurement	Particle size		
	Propeller driven	Conventional method	Stickiness	Mango, coffee, tomato soup powder,	[156]
	Glass transition temperature	Indirect method	Stickiness	Coffee, food powder	[157,158]
	Texture analyzers	Stress-to-strain ratio	Texture profile, hardness, cohesiveness, adhesiveness, etc.	Asparagus	[159]
	Vibration measurements	Probe driven by electromagnetic energy and microphone-based technique	Firmness	Tomato	[160]
	Acoustic measure	0–50 Hz, >1000 Hz frequency analysis	Texture profile	Cucumber	[161]
	Impact response	Low-mass impact sensor, capturing of impact signal	Firmness	Tomato	[153]
	Micro deformation sensors	Force deformation curve, compression deformation	Firmness	Tomato	[162]
	Ultrasonic wave propagation	Continuous-touch ultrasonic system	Firmness	Tomato, apple	[163,164]
	Nuclear magnetic resonance	Cost extensive	Morphological, physical parameters, thickness		
	X-ray computed tomography	Non-destructive, microstructure analysis is possible, online inspection friendly	Overall quality, maturity	Sweet potato	[165]
	Fluorescence	Rapid, reliable, non-destructive	Texture, colour	Broccoli	[166]

Table 2. *Cont.*

Food System	Techniques	Key Feature	Quality Attribute	Application	Reference
Fruits and Vegetables	Time-resolved diffuse reflectance spectroscopy	Non-destructive	Texture	Tomato	[167]
	Laser-scattering imaging	Non-destructive	Firmness	Tomato	[168]
	Friction force microscope, atomic force microscopy, tribometer, contact profilometry, surface force apparatus	Surface contacting techniques	Surface texture	Potato	[169]
	Confocal laser scanning microscopy, fiber-optic reflectometer, gloss meter, surface glistening points method, angle-resolved light scattering	Non surface contacting techniques	Surface texture (average roughness, root-mean square roughness, average slope of surface asperities, peak to valley height)	Tomato pulp	[170]
	Near infrared (IR) technique	Hyperspectral imaging technique	Scattering and absorbance properties	Zucchini squash, tomatoes, cucumbers	[171]
	Resonant cavity method	Important for modelling of Microwave drying	Loss factor, dielectric constant	Garlic	[172]
	Thermistor-based method	Traditional method	Thermal conductivity	Potato	[173]
	CT meter	Easy operate	Thermal Diffusivity, thermal conductivity	Onion powder	[174]
	High-speed IR camera	Rapid, non-destructive	Thermal Diffusivity, thermal conductivity	Onion	[175]
Cereal Product	Numerical methods (NM)	Better insight to predict anomalies that are difficult to predict using analytical approaches since it can only answer a few (2 to 3) unknown variables, whereas NM can do much more.	The grain-to-wall friction coefficient, internal friction angle, specific weight	Silo design	[176]
	Triaxial test, uniaxial compression test		Modulus of elasticity	Cereal grain	[177]
	Acoustic method	Estimation of acoustic shear wave	Modulus of elasticity	Cereal grain	[178]
	Computed tomography (CT), ultrasound, electrical tomography (ET), MRI	Non-destructive technique	Perimeter, Elongation, Area, compactness, maximum width, maximum length,	Barley, rice	[179]
	Scanning electron microscopy (SEM), confocal laser scanning microscopy	Stereospecific vision, higher magnification and resolution	Microstructure	Rice, wheat	[180]
	Manometric, gravimetic, hygrometric	Manual process, frequent calibration is required, not work properly at frost point	Equilibrium moisture content, moisture sorption isotherms (MSI)	Rice, grain, barley	[181]
	Dynamic vapour sorption	Gravimetric technique, water vapour and organic solvent can be used	Equilibrium moisture content	Mushroom	[182]

Table 2. *Cont.*

Food System	Techniques	Key Feature	Quality Attribute	Application	Reference
Cereal Product	Gravimetric method	Time consuming, the ion to be investigated should be fully precipitated. It must be a pure chemical that forms the precipitate. Filtration of the precipitate should be simple. The precipitate should have a low solubility and a high purity.	Water diffusivity	Cereal grain	[183,184]
	MRI, Diffusion-weighted imaging	Noninvasive	Water diffusivity	Cereal grain	[185]
	Farinograph, mixograph	Torque measurement, mixing property	Development time, Water absorption, Degree of softening, Stability	Dough	
	Consistograph	Pressure measurement, mixing property	Stability	Dough	
	Extensigraph	Uniaxial resistance to extension, Deformation Behavior	Energy, extensibility ratio, tenacity	Dough	
	Alveograph	Biaxial resistance to extension, Deformation Behavior	Extensibility Ratio, Work of deformation Tenacity,	Dough	
	Amylograph, Viscograph, Falling number, Rapid Visco-analyser, Mixolab	Apparent viscosity, Pasting Properties	Gelatinization properties, Amilase activity	Dough	
	Continuous progressive compression	At a constant amplitude of vibration, the sample was gradually compressed. On the compression curve, the compression force at the instant when the plunger distorted the grain was continually recorded.	Hardness, stickiness	Rice, wheat, noodles and bread	[186,187]
	Jet impingement, microwave-jet impingement, microwave-infrared, SEM, liquid extrusion porosimetry, volume displacement, pycnometry		Fraction of closed, total porosity, pore size distributions, blind and flow-through pores	Bread	[188]
Meat, Fish and Poultry	Surface electromyography	Recording of electrical signal	Muscle fiber composition and diameter	Lamb, pig	[189]
	Image analysis, video image analysis	Non-invasive	Colour, curvature, angle, volume, linear measurements, marbling	Beef	[190,191]
	Ultrasound	Non-invasive	Marbling, longissimus muscle	Beef	[192]
	Spectrophotocolorimeter, colorimeter	Color Reflectance, for external colour	Lightness, redness, yellowness, chroma, hue	Beef	[193]
	Optic probes	For internal colour	Lightness, redness, yellowness, chroma, hue	Beef	[194]

Table 2. *Cont.*

Food System	Techniques	Key Feature	Quality Attribute	Application	Reference
Meat, Fish and Poultry	Visible and near-infrared spectroscopy	Non-destructive	Tenderness	Beef	[195]
	Bioelectrical impedance analysis, electrical conductivity, magnetic inductance technology	Non-destructive	Fat and lean content	Lamb	[196]
	X-ray CT	Lower cost alternative	Average density and area		[197]
	Warner-Bratzler shear force (cooked meat), compression test (raw meat), Texture Analyzer	Invasive method	Rheological properties	Beef	[198]
	Beefcam	Simplified, useful in commercial application	Tenderness	Beef	[199]
	Optical reflectance	Measurement of physical characteristics	Tenderness	Beef	[200]
	Bite tests, penetrometry, tensile test	Invasive method	Tenderness	Beef	[201]
	Digital image analysis	Non-invasive method	Surface texture, Colour, marbling	Beef	[202]
	X-ray microtomography	Non-invasive method	Intramuscular fat	Beef	[107]
	Hyperspectral imaging	Non-invasive method	Colour, marbling, drip loss	Pork	[203]
	Viscometer	Fluid friction measurement	Viscosity	Low-fat meat batters	[204]
	Finite element method	Computer simulation model	Thermal conductivity	Meat emulsion	[205]
	Image analysis	Non-invasive method	Visual appearance, taste, texture	Ham	[206]
	Lacunarity analysis, variogram	Non-invasive method	Fat-connective tissue, pores	Ham	[206]
	NIR spectroscopy	Provide results closer to true quantitative value and fast method	Brightness, oiliness	Iberian pig fat	[207]
	Differential scanning calorimetry	Non-invasive and fast method	Melting properties, thermal behaviour	Dry cured ham	[208]
Dairy product	Static light scattering (Malvern Mastersizer)	Measurement of refractive index	Particle size	Milk powder	[209]
	Powder tester		Cohesion, Compressibility, Packed, and Bulk densities, angle of spatula, angle of repose	Milk powder	[210]
	Micromeritis pycnometer	Measured by the change in gas pressure	Density and volume	Milk powder	[211]
	Shear cell technique	Traditional method	Wall friction, internal friction, flow function	Milk powder	[212]
	Annular shear cell		Effective angle of internal friction, flow function	Milk powder	[209]
	Angle of repose	Static measure of relative flowability	Flow function	Milk powder	[213]
	Pneumatic techniques	Direct method	Cohesiveness, adhesiveness, sticky-point temperature	Milk powder	[214]

Table 2. *Cont.*

Food System	Techniques	Key Feature	Quality Attribute	Application	Reference
	Propeller-driven method	Simple, easy to use	Sticky-point temperature	Milk powder	[215]
	Ampule method	Simple, easy to use	Surface caking temperature	Milk powder	[216]
	Unconfined yield test	Simple, easy to use	Cohesiveness	Milk powder	[217]
	Viscometer technique	Provide results closer to true quantitative value and simple	Stickiness, torque	Milk powder	[215]
	Force–displacement cake strength determination	Easy to use	Caking strength	Milk powder	[209]
	Particle-gun method	Venturi funnel arrangement	Stickiness	Milk powder	[218]
	Fluidized bed rig	Easy to use	Sticky-point	Milk powder	[219]
	Cyclone test	Rotary motion generation	Stickiness	Milk powder	[220]
	Thermal mechanical compression test	Thermal compression test	Glass–rubber transition	Milk powder	[214]
	Rheometer	Rheological technique	Glass–rubber transition	Milk powder	[221]
	Static and dynamic wetting tests	Easy to use	Wettability	Milk powder	[213]
	Rehydration method, NMR relaxometry	Simple, easy to use	Solubility index	Milk powder	[210]
	Confocal scanning laser microscopy, SEM, X-ray photoelectron spectroscopy	Stereospecific vision, higher magnification and resolution	Microstructure	Milk powder	
Dairy product	Melting thermogram	Easy to use	Melting behaviour	Butter	[222]
	Nmr	On-line phase transition monitoring	Phase transition temperature	Cream	[223]
	Ultrasonic velocimetry, pulsed NMR, ultrasonic spectrometry	Online crystallization process monitoring	Solid fat content	Anhydrous milk fat	[120]
	Penetrometry test	Easy to use	Textural property, Adhesiveness	Butter	[222]
	Texture analyzer with a rig	Easy to use	Spreadability	Butter	[224]
	Parallel plate rheometer, scraper-rheometer	Easy to use	Viscoelasticity	Butter	[222]
	X-ray diffraction	Non-invasive method	Crystallinity	Butter	[225]
	Brookfield viscosity				[226]
	Drainage	Spontaneous, easy to use	Water-holding capacity	Butter	[226]
	Oscillatory rheometry, viscosity, turbidity, dynamic light scattering, thromboelastography, electrical conductivity, vibrational viscometry, thermal conductivity near-infrared spectroscopy, refractometry, diffusing wave spectroscopy, microscopy, electroacoustics, fluorescence spectroscopy and low- and high-frequency ultrasound	Rapid	Curd setting, textural property	Cheese	[227]

Table 2. *Cont.*

Food System	Techniques	Key Feature	Quality Attribute	Application	Reference
Dairy product	Bending test, Puncture, wire cutting test, dynamic and transient oscillation, uniaxial compression, cone penetration, torsion	Rapid	Springiness, hardness, cohesiveness, adhesiveness	Cheese	[209]
	Centrifugation, gravity loss	Higher variability between results	Water retention capacity	Cheese	[228]
	Cryo SEM, fluorescence microscopy	Stereospecific vision, higher magnification and resolution	Microstructure	Ice-cream	[229]

12. Conclusions

Mainly traditional/conventional and some novel analysis techniques have been considered here. The conventional methods are easy to implement and are cost effective, and the instruments are easily available. Thus, they are widely acceptable in industry. Conventional analysis methods applied to examine the physical properties of food material are associated with several disadvantages, such as their destructive nature, long process time, and laborious nature. To mitigate these limitations, it is extremely important to use novel technologies like MRI, NMR, UDV, acoustic methods, CT, and sensor-based methodologies. Several emerging techniques have been employed to characterize the physical properties of food materials. It has been observed that not only are they non-destructive in nature, but the results are also closer to the true quantitative values. Although several emerging techniques currently in use are discussed in this work, the replacement conventional methods with novel techniques must be developed at a faster rate.

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