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Review Article

Cutting edge technologies for the evaluation of plant-based food and meat quality: A comprehensive review

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Abstract

Assessing the food quality is essential to confirm the safety, nutritional value, and sensory attractiveness of the food we ingest. Due to the globalization of food industry and concerns over food security have resulted to a greater demand from consumers for safe and nutritious food. As a result, there is a need for manufacturers to develop cutting edge technologies for recognizing and determining food quality. Presently, stakeholders in the food industry encounter the challenge of ensuring food quality and safety. Producers need to meet sustainable and environmentally robust food production standard, extended shelf life, sensory quality, nutritional value, and functional properties. The general analytical practices identify the primary metabolites for whole food quality which solely verifies the total composition of nutritional metrics. In present days consumers concentrate of functional quality of food items. So, it is essential to examine secondary metabolite compounds, enzymes and other functional quality, authenticity of food items, sources that are critical for health, development, safety, and other aspects of consumer well-being. This review paper seeks to examine the different aspects of evaluating food quality and the methods used to ensure that the food we consume meets the required criteria. Furthermore, it discusses cutting edge technologies for assessing especially secondary metabolites, enzyme functions, functional quality of food items, verifying food authenticity to optimize food manufacturing processes.

Introduction

Worldwide human population assumed to be 10 billion and more by 2050, accompanied by an increased demand of foods and doubling in meat consumption (FAO, 2017). According to FAO the acceleration of income in developing countries would lead to a dietary transition characterized by increased food consumption and especially of meat. The rise in food demand has given rise to apprehensions regarding maintain quality control. The quality and safety of food are essential factors that pertain to all food products and hold significant economic importance. Analyzing the characteristics and composition of raw materials and food products is essential to guarantee food safety and quality, as there is an increasing focus on these concepts from both the food industry and consumers. Various elements influence the overall quality of food, starting from its source, cultivation method and processing, as well as its storage and preparation. The pricing of any kind of food product is mediated by the brand value and quality. Peri defined the term food quality as "fitness for consumption". Food quality encompasses both external and internal variables, such as dimensions, color and uniformity in size/shape, texture, taste, flavor, smell, chemical composition, functional characteristics, and microbes. Within this set of elements, specific attributes such as appearance can be visually recognized or sensed, while other attributes like chemical substances necessitate analysis using specialized instruments (Zhong & Wang, 2019). Significant evaluation tools have been developed and frequently deployed to comprehensively assess foods quality as shown in figure 1.

The interest in characterizing and quantifying the primary and secondary metabolites of foods has risen due to their beneficial therapeutic effects. Scientific studies conducted to assess the nutritional value, purity, and authenticity of food materials. As a result, foodomics technologies have started (Bevilacqua et al., 2017). Foodomics is a relatively new field that focuses on using modern omics technology to study food and nutrition. Its objectives are to enhance consumers' health and confidence (Herrero et al., 2012). Due to the wide variety of food primary and secondary metabolites and their diverse characteristics, different analytical approaches have been established for each category of compounds. These methods vary right from the initial stage of extracting the metabolites (Giordani et al., 2011). To provide consumers with comprehensive information on the functional properties of different meals, both primary and secondary metabolites necessitate a specialized extraction and analysis methodology (Acquavia et al., 2021).

Food market globalization and increasing consumer demand for safe food need cutting edge techniques to assess food quality. In present days, food producers are facing the task of ensuring the quality and safety of food more complicated due to additional compliances and functional qualities of food items (Andre & Soukoulis, 2020). In addition, food fraud related to deliberate product mislabeling or economically intended adulteration is of major concern for both industry and regulatory authorities due to cost and public health implications. Food fraud or adulteration is a known term in this industry and have become more frequent and the majority of them have an economic ground (Hong et al., 2017). A typical example of food fraud is melamine incorporation into raw milk, powdered infant formula, and cereal-based formulations in various countries to boost their total nitrogen concentration (Zhang & Xue, 2016). The incorporation of both water and sugar in honey a food with high economic value, is a widespread occurrence (Soares et al., 2017). These instances represent as typical examples of monetarily driven frauds in high-value food products, causing customers to question the authenticity of their food. Chemometric tools efficiently can be used to detect food frauds or misdeclaration.

Now a days, chemometrics, multivariate data analysis, and univariate or multivariate regression modeling, are frequently used in food process optimization and food quality assessment (Varmuza & Filzmoser, 2016). Multivariate regression modelling was successfully applied in food authentication process and food quality assessment of chevon (M. Hashem et al., 2022). Chemometric techniques have been used to extract useful information from interference, reveal concealed connections, and offer a graphical approach for analyzing multivariate data (Granato et al., 2018). Chemometric tools efficiently can be used to detect food frauds.

At the end of the day food products should be subjected to strict quality controls. The reason behind this is the changing demand of consumers on special attributes of foods rather than protein, sugar, fat etc. moreover it has to be considered that different food materials requires different kinds of analytical techniques based on their composition and the target compound. In recent days cutting edge technologies have become extremely appealing than the ordinary chemical analysis and these new methods has substantially improved the capability to reveal and understand the in-depth composition of food. Bearing all the above context in consideration This review paper has tried to emphasize more on the noble and cutting-edge technologies in practice to evaluate the food quality. Moreover, special emphasize has given on secondary metabolites, enzymes, functional quality of food items and food adulteration.

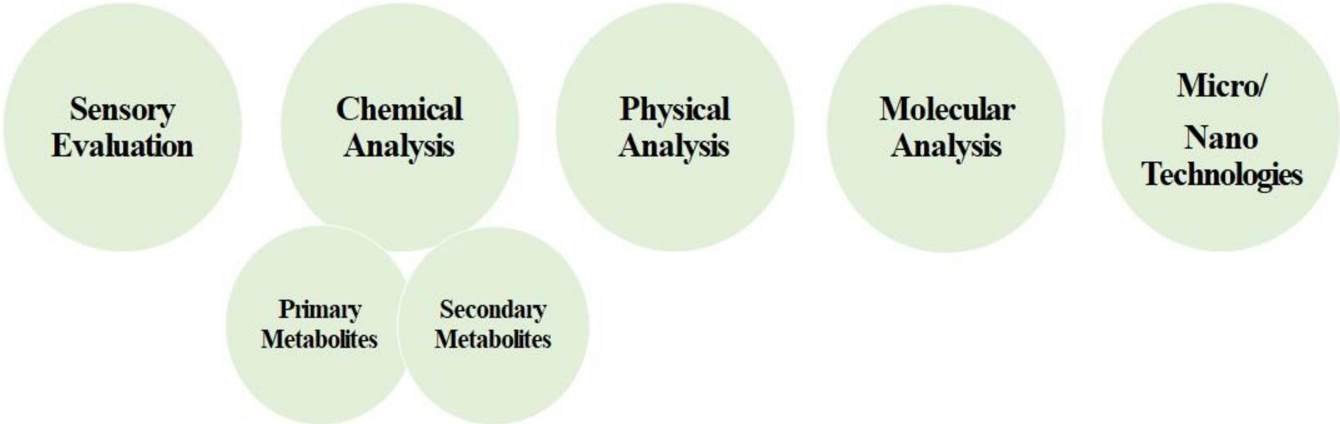

Figure 1. Types of food quality assessments.

Sensory quality of foods

The sensory attributes of food serve an essential function in the modern food industry, as the superior taste and texture of a product is vital for achieving success in today's highly competitive marketplace. For food items, the assessment of sensory quality continues to rely mostly on physical inspection. However, this technique is burdensome, time-consuming, and expensive. Moreover, it is prone to the influence of physiological factors, which leads to subjective and inconsistent evaluation outcomes. In order to meet the increased awareness, sophistication, and elevated expectations of consumers, it is vital to improve the evaluation methods of food product quality (Brosnan & Sun, 2004). Automation in food quality assessment will result in the alleviation of production speed and efficiency. Furthermore, there is an enhanced precision in evaluation, along with a concurrent decrease in production expenses. (Sun & Brosnan, 2003).

Consumer select foods on the basis of its color, flavor, nutritional value, safety, and sensory characteristics. Different types of analytical methods apply for the sensory quality control of food products. The objective of evaluating and controlling food items in real time during the production process has been suggested as being accomplished by the utilization of novel approaches such as electronic nose, electronic eye, and electronic tongue, as well as the integration of these technological devices (Chattopadhyay et al., 2014; Chen et al., 2015; Cubero et al., 2011; Yang et al., 2015).

The University of Warwick in the United Kingdom proposed the idea of an electronic nose system in 1982, as suggested by Dodd (Dodd et al., 1992). An electronic nose is designed to imitate the human sense of smell and has the capacity to recognize volatile aromas emitted from different sources (Deshmukh et al., 2015). The electronic nose is frequently used in the analysis of many substances such as meat, grains, tea, coffee, beer, milk, fish, fruits, vegetables, and many more (Sanaeifar et al., 2017). Electronic nose is of useful in assessing freshness and storage quality of food products in respect of food research and food industry (Dodd et al., 2004). Several studies conducted with electronic nose for the identification of aroma compounds (Frauendorfer & Schieberle, 2006) and employed for the quality control of Lonicera japonica during several months of storage (Xiong et al., 2014).

Taste is a crucial sensory characteristic that influences the acceptance of food for consumers, specifically humans (Latha & Lakshmi, 2012). An electronic tongue, referred to chemical taste sensor array, can be used to conduct taste analysis of food. This analytical sensory system allows for the rapid evaluation of sophisticated liquid systems (Toko, 1998). Electronic taste sensing is a method used in the food industry to evaluate the quality and monitor various samples. It is particularly useful for separating and recognizing similar samples, especially liquids (Rudnitskaya et al., 2017).

Another noble sensory analytical method is computer vision system which is a new artificial perception technique and a promising way of detecting the external characteristics of food. Compared to traditional detection methods, the computer vision system deals with food color, shape, size, and texture effectively. An electronic eye is a computer vision technology that relies on an image sensor to capture digital images of objects. It employs computer simulation criteria to precisely recognize these images, eliminating any subjective deviation that may occur with human eyes (Guo et al., 2017). The extensive utilization of this technology has proven its effectiveness as a fast, accurate, and non-invasive technique for assessing product quality in terms of shape, size, color, and texture analysis.

Secondary metabolites and food quality

Secondary metabolites are very diverse compounds that have gained significant importance in food industries and primarily, they are utilized for their bioactive properties. However, with advancements in analytical chemistry, procedures allow the authentication and critical quality control parameter for foods (Pedrosa et al., 2021). Secondary metabolites produced by plants are of immense importance in the food quality and used as antioxidants, bioactive and nutraceutical ingredients, and food additives (Delgado et al., 2019). Secondary metabolites produced by plants have been acknowledged for their medicinal potential. Medicines generated from plants have resulted in the discovery of numerous potential compounds that play therapeutic roles through different techniques (Kumar et al., 2022). These secondary metabolites derived from plants divided into four categories i.e., phenols/polyphenols, terpenes/terpenoids, Sulphur compounds and nitrogen compounds (Kumar et al., 2022).

Phenolics and polyphenolics are among the most important secondary metabolites and prevalent natural chemicals found in plant derived foods. Phenolic secondary metabolites have a significant effect on the quality of plant-derived food, impacting characteristics such as appearance, flavor, and health-enhancing effects. Particularly due to their vital role in preventing a variety of disorders, such as cardiovascular, neurological, degenerative disorders, and cancer. Phenolic stability, biosynthesis, and deterioration in food are influenced by many variables that impact their content. Epidemiological studies suggest that consuming a substantial quantity of fruits and vegetables can aid in preventing chronic cardiovascular disease and certain types of cancer, potentially due to the presence of phenolic chemicals. (Arai et al., 2000).

Phenolic compounds have a significant influence on the visual appearance of food. Anthocyanin pigments are responsible for the vast majority of the blue, purple, red, and intermediate shades found in plant-based meals, and they may appear as a "black" color in certain products. (Tomás-Barberán & Espín, 2001). Tables 1 provide an overview of the anthocyanin pigments that give diverse fruits their color. Their hue and structure are dependent on the pH value and the presence of co-pigments (Brouillard et al., 1997). In majority of cases, an augmentation in anthocyanin pigmentation is considered as a desirable characteristic of plant-based foods, leading to the development of more colorful fruits, berries, and wines. However, there are examples where this pigmentation is seen as undesirable, such as in the case of asparagus tips (Horbowicz et al., 2008).

Phenolic compounds have significance role in food flavor and can influence the bitter, sweet, spicy, or astringent taste of some items and also contribute to scent. Certain substances, after chemical conversion to their respective dihydrochalcones, demonstrate a high level of sweetness (2000 times sweeter than sucrose) and are commonly employed as potent sweeteners (Baker & Cameron, 1999). Coumarins, including 6-methoxymellein, have been found for the bitter taste in carrots after they are damaged (Mercier & Kuc, 1997).

Food quality changes with changes in the quality of phenolic compounds. Different factors affecting the quality and quantity of phenolic compounds are showed in figure 2. The phenolic content of plants is significantly influenced by the amount of water during irrigation and the nature of the soil, particularly including its mineral and organic nutrient content (McClure, 1975). The handling of fruits and vegetables includes several stages such as harvest, transportation, storage, heat treatments, pressing, enzyme treatment, fermentation, and cooking (Häkkinen et al., 2000; Price et al., 1998), manual extraction of juice by applying pressure with the hand (Gil-Izquierdo et al., 2001; Häkkinen, Kärenlampi, Mykkänen, Heinonen, et al., 2000). Flavonoids are the most plentiful (up to 60%) and extensively investigated group of polyphenolic compounds because of their remarkable biological activities and therapeutic importance, which includes antioxidant, anticancer, antimicrobial, anti-inflammatory, immunomodulatory, vasodilating, and prebiotic properties (Sharma et al., 2019). Flavonoid-rich foods are considered as potential therapeutic and food supplements for the prevention and treatment of several diseases and human afflictions (Boniface & Ferreira, 2019).

The non-flavonoid compounds possess structures that exhibit a wide range of variation. These compounds have attracted significant interest due to their usage being associated with various healthcare benefits. In particular, they have been found to reduce the prevalence of chronic degenerative diseases such as Alzheimer's disease, cancer, heart diseases, and diabetes (Kumar et al., 2022). Coumarins, isocoumarins, and chromones are non-flavonoid chemicals that are found in plants and have a wide distribution. These compounds have been identified for their antioxidant, antibacterial, anti-inflammatory, and anticancer properties (Shahidi & Ambigaipalan, 2015). Anthraquinones are commonly used as natural colorants (Malik & Müller, 2016), Curcuminoids are a significant non-flavonoid molecule that serves with therapeutic benefits (Li et al., 2019).

Alkaloids are a prominent group of secondary metabolites and biologically active substances that are abundantly found in several medicinal plants, specifically in leaves, bark, or roots with high concentrations. Approximately 20% of flowering plants possess alkaloids, which exhibit medicinal, addictive, and toxic properties. These alkaloids have been observed to be linked with the survival of plants in the environment. Prominent alkaloids include morphine, strychnine, quinine, ephedrine, and nicotine (Kumar et al., 2022). Sulfur-containing compounds are an essential category of secondary metabolites that possess a unique smell and serve as defense chemicals against herbivores and pathogenic organisms (Kumar et al., 2022).

Table 1. Type of anthocyanins in fruits responsible for the color

Fruit	Available Anthocyanins (Brouillard et al., 1997)	Intended consumer use
Apple	cyanidin	Fresh
Apricot	cyanidin	Fresh
Blackberry	cyanidin	Jam, frozen.
Blueberry	Delphinidin, malvidin, petunidin, cyanidin, peonidin	Jam, juice, frozen
Cherry	Cyanidin	Fresh
Cranberry	Cyanidin	Juice, jam, frozen
Currant (red)	Cyanidin	Juice, jam, frozen
Currant (black)	Cyanidin	Juice, jam, frozen
Fig	Cyanidin, Pelargonidin	Fresh
Grape	Delphinidin, petunidin, cyanidin, malvidin	Fresh, wine
Litchi	Cyanidin, malvidin	Fresh
Mulberry	Cyanidin	Juice, jam, frozen
Olive	Cyanidin	Pickled
Orange	Cyanidin, Delphinidin	Juice, fresh
Passion fruit	Delphinidin	Fresh
Peach (nectarine)	Cyanidin	Fresh
Pear	Cyanidin, Peonidin	Fresh
Plum	Cyanidin	Fresh
Pomegranate	Delphinidin, Pelargonidin	Fresh, juice
Raspberry	Cyanidin	Fresh, frozen, juice, jam
Strawberry	Pelargonidin, Cyanidin	Fresh, frozen, juice, jam

Secondary metabolites analysis

The extraction and analytical measurement of secondary metabolites are of the utmost importance due to their significant value and interest. Currently, a wide range of extraction techniques are employed. But the choice of the technique depends the target metabolite, experimental design and the subject or purpose of the study or application. Those methods include solvent extraction, microwave-assisted extraction, ultrasonic extraction, solid phase extraction, and molecularly imprinted polymers are appropriate to extract all phenols and secondary metabolites. Additional techniques that target the extraction of thermolabile, non-thermolabile, or less polar phenolics include enzyme-assisted extraction, pressurized liquid extraction, and supercritical fluid extraction, respectively (Delgado et al., 2019). Various techniques have been developed to identify, quantify and assess the phenolic substances. These procedures rely on various factors, including the chemical properties of the target compound, the extraction technique employed, the duration and circumstances of storage, the size of the particles, the choice of standards, the presence of irrelevant elements and the presence of contaminants (Li et al., 2017).

Spectrometric methods are frequently employed for quantifying the total phenolics, total flavonoids, and total anthocyanins contents. While these procedures are fast and easy, they do not have the level of accuracy to distinguish between particular chemicals. Due to the progress of analytical sciences, there has been rapid development in equipment and techniques. Currently, there is a wide range of tools at our disposal, including HPLC, GC, LC-MS, GC-MS, and nuclear magnetic resonance (Delgado et al., 2019). Table 2 explains the use of different methods used for secondary metabolites analysis during research experiments.

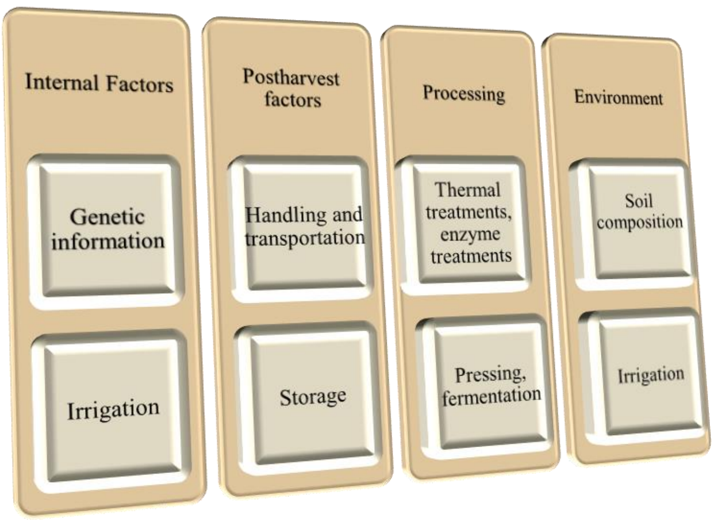

Figure 2. Factors affecting the phenolic metabolites composition of food.

Table 2. Different analytical methods used for secondary metabolites assessment

Method	Observations	Reference
Spectrophotometric method	Rapid, simple, precise and reproductible method	(Pueyo & Calvo, 2009)
Enzymatic spectrophotometry	Costly	(Kumar et al., 2022)
Near-infrared spectroscopy	Efficient, rapid, non-invasive analytical instrument.	(Brglez Mojzer et al., 2016)
HPLC	The technology most frequently employed to acquire information on the molecular mass and structural properties of analytes is considered to be more favorable than other techniques.	(Brglez Mojzer et al., 2016)
GC	A highly efficient technique for the isolation, characterization, and quantification of various phenolic groups, including phenolic acids and flavonoids.	(Brglez Mojzer et al., 2016)
HPLC-UV detection	Less costly, user friendly and appropriate for regular analysis.	(Brglez Mojzer et al., 2016)
Capillary electrophoresis	Efficient, faster speed, less strict sample purification, and minimal solvent application.	(Arráez-Román et al., 2006; Delgado et al., 2019; Moreno-González et al., 2015; Nicolaou & Kapnissi-Christodoulou, 2010; Rizelio et al., 2012)
Biosensors	Ability to work in real time, portable option, precision in its function, ease of automation and high sensitivity.	(Antunes et al., 2018)

Functional quality of food

The growing consumer consciousness and drive for wellness, health, and nutrition has resulted in an increased demand for food products that promote health and prevent diseases (Alam et al., 2024a; Alam et al., 2024b; Samad et al., 2024, Jakir et al., 2024, Kumari et al., 2023). These products, commonly referred to functional foods, contain bioactive components that offer health benefits beyond basic nutrition (Saleh et al., 2013). The functional attributes of some secondary metabolites are elaborated in table 3. Bioactive components including phytochemicals, dietary fibers, and proteins give functional foods physiological benefits like boosting the nutritional value of certain foods and reduce the risk of lifestyle-related degenerative illnesses (Olaiya et al., 2016). Functional foods are subject to special regulatory regulations and necessitate different safety criteria in contrast to dietary supplement ingredients (Griffiths et al., 2009). It is important to emphasize that functional food is a type of food that is included in a person's usual daily diet (Bazhan et al., 2017). Therefore, the fundamental characteristics and analytical techniques of functional food cannot be distinguished from that of conventional food and would be the same.

Table 3. Functional attributes of some secondary metabolites

Food	Functional activity	Major secondary metabolite	References
Brown rice	Elevated levels of catechin and total flavonoid content in brown rice resulted in enhanced antioxidant activity and anti-cancer capabilities.	Catechin	(Brotman et al., 2021)
Soy bean	High levels of isoflavones and saponins in soy have proven anti-inflammatory, anti-carcinogenic, and cardioprotective attributes.	Isoflavones, Saponins	(Guang et al., 2014)
Functional Bread	Bread comprised of wheat, malted millet and okara flour contain higher protein, calcium, magnesium, phosphorus, and sodium contents than regular flour bread. Additionally, higher dietary fiber, phenol and flavonoid content made it better antioxidant active bread than regular one.	Phenols, Flavonoids.	(Ibidapo et al., 2020)
Spinach	Spinach possess better antioxidant and anti-inflammatory properties due to high flavonoid content.	Patuletin, Spinacetin, Spinatoside, Jaceidin, and Flavone	(Koh et al., 2012)
Tomato	Usually tomato and tomato food products constitute majority lycopene in human diet and is a critical component for the production of beta-carotene and xanthophylls.	Lycopene	(Ruiz-Sola & Rodríguez-Concepción, 2012)
Broccoli	Broccoli is high in polyphenols and sulfur compounds, which have been found to possess strong anti-cancer qualities and enhance heart function, hence decreases the risk of myocardial infarction.	Glucosinolates, Isothiocyanates, Isorhamnetin, Sinapic acid, Quercetin.	(Essa et al., 2023) (Damon et al., 2005; Mukherjee et al., 2008)
Nuts	People consuming nuts regularly have less incidence of cardiovascular diseases and diabetes.	Phenolic compounds and Flavonoids	(Jiang et al., 2003; Kris-Etherton et al., 2008)
Blueberries	Anthocyanins is the major (Approximately 60%) component in blueberries and have the ability to lower the risk of hypertension in women, boost vascular function, and aid in weight maintenance.	Anthocyanins	(Bertoia et al., 2016)
Pomegranate	Pomegranate having antioxidant and anti-inflammatory activity.	Flavonoids, Lignans, Polyphenols, Anthocyanins, Tannins, Terpenoids, and Sterols	(Vučić et al., 2019)
Fish	Sea fishes contains a higher amount of Eicosapentanoic acid (EPA) and docosahexaenoic acid (DHA) and are essential component of cellular membranes in brain and retina.	EPA, DHA	(Alam et al., 2011; Wergeland et al., 2012)

Enzymes and Food quality

Enzymes play a critical role in food quality parameters. The assessment of enzymatic activity and concentration is valuable for evaluating the effect of physical or nutritional changes on the quality characteristics of food (Kaur & Kaushal, 2023). The current analytical techniques in the food sector are labor-intensive and time-consuming, reliant on skilled workers. These approaches depend on lengthy separation methods, costly apparatus, and highly pure chemicals. Compared to conventional physical and chemical methodologies enzyme based analysis is more precise (Prodromidis & Karayannis, 2002).

Enzyme immunoassay technique like ELISA (enzyme-linked immunosorbent assay) are precise and sensitive and frequently employed in plant pathology, medicine, and especially in the food industry for the purpose of quality control and assessment (Samarajeewa et al., 1991).

A standard procedure in milk pasteurization process is alkaline phosphatase (ALP) test. In this test the thermal inactivation characteristics of ALP enzymes are analyzed (Rankin et al., 2010). ALP test is effective for quality assessment of milk products like powdered milk, cheese, cream, and ice cream. (Balkishan et al., 2010; Rajan et al., 2009). Blanching is an essential step for vegetable and fruit processing. In blanching process enzymes such as polyphenol oxidase and peroxidase are deactivated in order to prevent impaired taste and undesired color changes (Nurhuda et al., 2013; Wang et al., 2017). Enzyme related techniques now practices in biosensor devices, which is a bio specific recognition system, for cells, enzymes, antibodies, or proteins, to precisely analyze the concentration of target analytes (Schaertel & Firstenberg-Eden, 1988). The mode of action in biosensors are using enzymes to track the analytes based on tracking analytes with enzymes (Akyilmaz et al., 2010).

Metabolomics

Metabolomics is a new arena for the identification of small molecular metabolites in the biological systems and is commonly applied in the evaluation of food quality (Kuehnbaum & Britz-McKibbin, 2013). Metabolomics enable the monitoring of metabolite that changes during food processing aid in the optimization of nutritional value. There are several variables for example species, environment, processing methods, storage procedures etc. influence food metabolites (Farag et al., 2022). Furthermore, these changes of metabolites directly influence the safety and quality of food items. Metabolomics technology can be utilized to identify and verify potential contaminants and drug residues in food processing to safeguard human well-being (Johanningsmeier et al., 2016).

There is a rise in the application of metabolomics in the food industry and it is aided by cutting edge technologies like ultra-performance liquid chromatography, capillary electrophoresis and matrix-assisted laser desorption (Chen et al., 2021). Standard database information from Wiley, Fiehn, Golm Metabolome Database etc. can be accessed to rapidly determine relevant metabolites (Putri et al., 2022). A snapshot of the use of metabolomics techniques summarized in Table 4.

Table 4. Cutting edge techniques for metabolomics analysis

Platform	Sample	Result/Objective	References
LC-MS/MS	Almond	Determination of aflatoxins excluding purification	(Ouakhssase et al., 2021)
UPLC-QTOF/ MS	Pomegranate juice	Detection of adulteration or mixing of other juices like apple and grape in pomegranate juice.	(Dasenaki et al., 2019)
ESI-MS/MS	Coffee bean	Pesticides and mycotoxins detection in coffee beans was successfully conducted.	(Reichert et al., 2018)
NIR	Rice	Detection of purity of rice when adulterated with other types of rice.	(Reichert et al., 2018)
NIR	Beef	Detection of added other species of meat in beef (pork, fat and offal) with 100% accuracy.	(Morsy & Sun, 2013)
UPLC-Q/TOF-MS	Fish sauce	A total of 46 metabolites has been identified to be the essential chemical constituents that contribute to the flavor of fish sauce.	(Wang et al., 2019)

State-of-the-art methods for meat and meat product quality assessment

Meat and meat products are essential part of the agri-food business and it constitute a significant component of individuals' daily dietary intake. Meat is an important component of human diet and contains key nutrients such as protein, fat, vitamins, and micronutrients. Furthermore its crucial role in promoting and maintaining excellent human health (Bithi et al., 2020; Disha et al., 2020). The topic of meat quality has garnered attention from stakeholders in the meat industry and health-conscious customers due to its impact on profitability (Disha et al., 2020). The rise in demand has given rise to apprehensions regarding the industry's capacity to efficiently oversee meat production and maintain quality assurance. The desire for higher quality meat products has increased among consumers due to improvements in living conditions. Differentiating meat quality is seen as a crucial aspect for achieving success in the market (Disha et al., 2020). Hence, it is essential to rigorously monitor these factors in order to guarantee the sustainability and safety of the meat business.

The fast increase in the demand for meat and the sophisticated supply chain complex framework created the demand for traceability (Mottola et al., 2023). The probability of food fraud and mis declaration increased along with the rapid expansion of e-commerce business. Mixed meat products like sausage, nuggets, patties are typically targeted for adulteration (Boby et al., 2021; Hassoun et al., 2020; Mottola et al., 2023). Food frauds, which involve the substitution of species partially or completely, are typically carried out to increase economic revenue. This is done by replacing premium species with cheaper ones or even illegally traded substitutes like vegetable proteins (Barbarossa et al., 2016). Conversely, inadvertent species substitution may arise due to unintentional cross-contamination in processing factories that utilize the similar processing area, equipment, materials and technology to make various meat products, or due to improper human handling (Keyvan et al., 2017). The authentication of meat products is obviously different than regular chemometric analysis and relies on the implementation of control systems, which utilize different techniques methods such as molecular analysis, chromatography, spectroscopy, spectrometry, and imaging approaches (Fengou et al., 2021; Hashem et al., 2022a; Ropodi et al., 2017).

Computer imaging technique

The imaging methodology is advantageous over common analytical methods in that it can visually depict the distribution of the variables being examined (Tarlak et al., 2016; Turgut et al., 2014). Computer vision system was useful to perform color analysis in beef (Tarlak et al., 2016). Researchers applied imaging technology to determine the water retention capacity of beef as well (ElMasry et al., 2012; Monroy et al., 2010). A computer imaging system was used to predict the quality in chicken sausage. The efficacy of the imaging technology was evaluated by means of calibration and statistical validation models. The model demonstrated that the imaging technique had the capacity to supplant the laborious, costly, and risky analytical technology in assessing beef chemical properties (Rahman et al., 2023). Hyperspectral imaging technology is more sophisticated technique and used to assess the qualitative characteristics of meat (Qiao et al., 2007). Furthermore, near infrared (NIR) imaging (ElMasry et al., 2011), and nuclear magnetic resonance (NMR) (Bertram et al., 2006) also very precise techniques that are used in meat quality analysis.

Near Infrared Spectroscopy (NIRS)

Near Infrared Spectroscopy (NIRS) presents an appealing alternative to the expensive and laborious conventional chemical analysis for assessing the quality of meat products. Multivariate partial least square regression (PLSR) model was developed successfully to forecast the chemical attributes of meat items by using NIRS spectra, where NIRS expressed the capacity to accurately predict the quality of meatballs. Furthermore, NIRS would be advantageous implications for both consumers and meat industry in terms of enhancing quality control (Hashem et al., 2023)

Advancements in microfabrication and miniaturization techniques have facilitated the production of portable spectrophotometers that are small enough to fit in the palm or pocket. NIR spectroscopy and multivariate analysis can be used for the rapid analysis of physicochemical parameters like moisture, drip loss, dry matter content, crude protein, ash etc. (Hashem et al., 2022b), intramuscular fat (Teixeira et al., 2015) efficiently. Dixit et al. (2020) demonstrated the quantification of intramuscular fat in lamb using micro NIRS. The combined application of portable NIRS and mathematical algorithms was used for the authentication of chicken meat (Parastar et al., 2020). In another study the efficacy of micro NIRS was tested to predict beef quality attributes (Hashem et al., 2021). The combination of NIR spectroscopy and PLSR can effectively be employed as a fast screening method for forecasting the quality of beef. In this study, the coefficients of determination (R^2 cv) derived from the established PLSR models for all quantifiable qualities were consistently over 0.90. The findings demonstrated that micro NIR spectroscopy exhibits promise as a non-invasive and expeditious technique for forecasting beef quality characteristics (Hashem et al., 2021).

Machine learning and meat fraud assessment

A substantial number of consumers on meat and its derivatives as vital components of their diet. Their nutritional value and taste made these consumers as “meat lovers”. Meat authentication according to species is crucial in order to guarantee the satisfaction and preference of meat type for consumers, in accordance with the regulations regarding meat and meat products (El-Shazly et al., 2016). The act of fraudulently mixing inferior quality meat with high quality meat has become an extremely common phenomenon of adulteration globally (Singh & Neelam, 2011). Adulteration includes both the substitution of substances and the dissemination of inaccurate information regarding the source of raw materials (Montowska & Pospiech, 2010).

The classification of meat based on species is vital in relation to its economic worth. The cost of premium meat cuts (sirloin) are significantly greater than that of less desirable cuts (shank and flank). According to a survey consumers' willingness to pay a higher price for tender steaks is an evidence of the significance of beef quality as premium meat (Kukowski et al., 2005). The high-quality cuts possess a wide range of attributes, including tenderness, juiciness, flavor, nutrient content, and overall meat quality profiles (Jung et al., 2016). These parameters are crucial for consumers when evaluating the quality of beef and making purchasing decisions (Henchion et al., 2014). The increased demand for this particular type of meat and especially beef, has resulted in fraud within the retail and supply chain sectors. These activities involve the replacement of high-quality beef cuts with lower-quality alternatives (Li et al., 2021), probably buffalo meat. Precise identification of species is essential in order to address meat fraud and satisfy the requirements of customers and food safety regulators.

To authenticate or identify any meat sample, a mathematical model can be build using multispectral imaging (MSI) and machine learning algorithm. In this process images of samples are captured using a multi-spectroscopic camera, which operates within the wavelength range of 500–800 nm to bring accuracy in classification model. Researchers usually apply single and multiple modality feature sets using different machine learning based classifiers, namely linear discriminant analysis (LDA), support vector machine (SVM), and random forest (RF) algorithms (Hastie et al., 1995).

Research revealed the potential use of machine learning algorithms in the field of meat categorization with an accuracy of more than 90 percent, specifically by combining various spectrum imaging approaches, which have important consequences for future agricultural uses (Li et al., 2021). By the implementation of machine learning with imaging values a number of novel beef cuts have been recognized like flat iron, Denver cut, chuck eye steak (Von Seggern et al., 2005). Furthermore, the deep learning neural network technique proved exceptional ability in accurately classifying flank steak and tenderloin in beef meat, with a classification accuracy of 100% (GC et al., 2021).

Artificial neural networks (ANNs) fall between engineering and artificial intelligence. An illustration of ANN is showed in figure 3. They employ quantitative techniques, such as minimizing mean-square error, but they also rely on intuitive approaches due to the frequent absence of theoretical foundations to guide conclusions about the development of artificial neural networks (Park & Lek, 2016).

Neural networks have applications for speech recognition, chemical process optimization, cancer cell identification, automatic handwritten character recognition, coin denomination recognition, and more (Ballard, 2004). The network builds a model based on examples in data with known outputs.

Artificial intelligence (AI) has been employed to figure out various objectives, including text/words, food categorization and identity verification systems (Buss, 2018; Jia et al., 2019; Liu et al., 2018). AI is famed for its efficacy, accuracy, dependability, and cost-efficiency, making it well fit for the meat industry's volume of production (Liu et al., 2018). Recent studies showed that AI technology has great potential to detect marbling in beef and pork (Chmiel et al., 2012), color of pork (Sun et al., 2018), tenderness of beef meat (Sun et al., 2012), and grading of beef according to fat color (Chen et al., 2010). Moreover, deep learning has been applied to bacon classification (Xiao et al., 2019) and classification of species in meat (Al-Sarayreh et al., 2020).

In addition, deep learning techniques have been implemented for the classification of bacon (Xiao et al., 2019) and the discerning of meat species (Al-Sarayreh et al., 2020). An authentication method using multispectral imaging (MSI) and machine learning-based classifiers showed that the model with multiple-modality fusion feature set beat the model using a single feature set, attaining prediction accuracy over 90% (Li et al., 2021). Therefore, the MSI technique could be suitable for implementing regular, nondestructive tests in the food business.

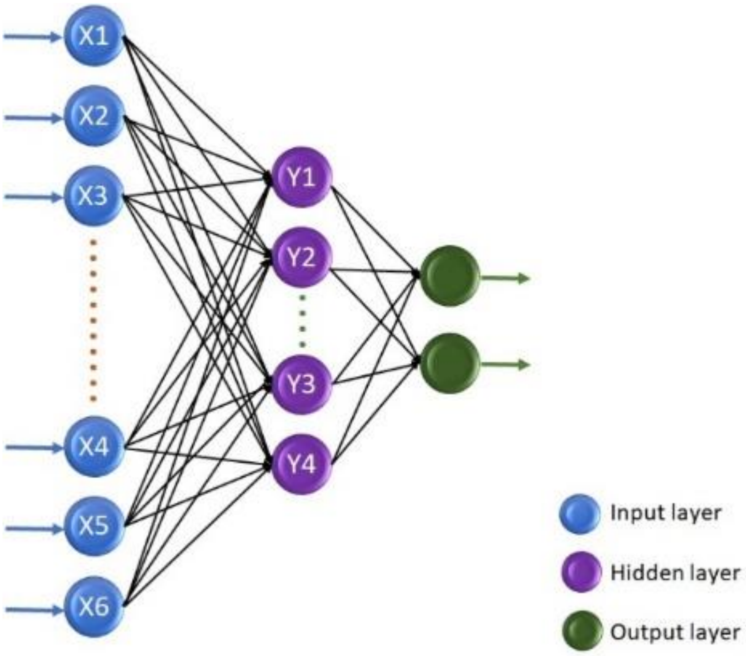

Figure 3. Illustration of ANN.

Conclusion

Plant foods and meat both are rich in biologically active macro and micronutrients that are critical for maintaining optimal human health. The technological and economic significance of plant food and meat quality extends beyond the food-processing industry to consumers, who consider it during making a purchase decision. The food industries are gradually adopting precise, quick and easy, online, cost-effective detection technologies. These advanced cutting-edge quality control techniques that are discussed in this review article are necessary in the food business to minimize economic losses during processing and provide a consistent supply of high-quality products. By utilizing a holistic approach of these techniques may assist consumers to make well-informed decisions, and producers can guarantee that the food they offer satisfies the utmost criteria. Nevertheless, consistent surveillance, strict compliance with rules, and ongoing enhancement of production processes are crucial for preserving and elevating food quality throughout the supply chain. Furthermore, Food fraud is escalating worldwide through deliberate efforts to deceive consumers for monetary benefit through the misrepresentation of food goods. This review suggests the utilization of synergistic methodologies like NIR and mathematical algorithms for the precise detection of various food products which will improve the authenticity and excellence of food products for higher consumer satisfaction.

Conflicts of interest

The authors declare that there are no potential conflicts of interest.

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