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PHENOLIC AND FLAVONOID PROFILING IN EDIBLE VEGETABLES: RECENT DEVELOPMENTS IN SPECTROSCOPIC ANALYSIS

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ABSTRACT
Flavonoids and phenolics are significant bioactive phytochemicals found in edible vegetables that have been shown to have antioxidant, anti-inflammatory, cardioprotective, anticancer, and neuroprotective qualities. Accurate characterization of these compounds is essential for nutritional evaluation, quality control, and functional food development. This review summarizes the occurrence of phenolics and flavonoids in edible vegetables and highlights recent advances in spectroscopic approaches used for their profiling and quantification. Literature published between 2016 and 2026 was examined with emphasis on extraction strategies and spectroscopic techniques, including UV–Visible spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, Near-Infrared (NIR) spectroscopy, Raman spectroscopy, fluorescence spectroscopy, Nuclear Magnetic Resonance (NMR) spectroscopy, and hyperspectral imaging. The role of chemometrics, metabolomics, and artificial intelligence in spectral interpretation was also evaluated. Recent technological developments have improved the speed, sensitivity, and reliability of phenolic and flavonoid analysis. Spectroscopic techniques combined with chemometric and machine-learning tools enable rapid, non-destructive, and high-throughput profiling of bioactive compounds in diverse vegetable matrices. Portable sensors and AI-assisted analytical platforms further support real-time quality assessment and monitoring. Spectroscopic methods have emerged as powerful alternatives to conventional analytical techniques for phenolic and flavonoid profiling. It is anticipated that further developments in sensor technology, data analytics, and artificial intelligence will bolster applications in functional food research, precision agriculture, and food quality assessment.

KEYWORDS: Phenolic compounds; Flavonoids; Edible vegetables; Spectroscopic analysis; Chemometrics.

1. INTRODUCTION

Edible vegetables are a key part of human nutrition and are well known to contribute to nutrition security and disease prevention. Vegetables offer a wealth of micronutrients, dietary fiber, and bioactive phytochemicals in addition to macronutrients, all of which play important roles in physiology and overall health. Regular vegetable consumption has been associated with a lower risk of chronic non-communicable diseases like diabetes, obesity, cardiovascular disease, and some types of cancer. The increasing trend towards plant-based nutrition has also underscored the need to know the chemical components that give vegetables their health-promoting properties. Of these, the phenolic compounds and flavonoids have been a subject of remarkable research due to their presence in large quantities, structural diversity, and biological activities (Frond et al., 2019).

The phenolics, a broad class of molecules with one or more aromatic rings and hydroxyl groups attached, are one of the biggest classes of secondary metabolites produced by plants. The flavonoids make up a large sub-class of phenolics, and are found throughout edible plant tissues. The compounds not only performance a role in plants growth, pigmentation and defense but also in the nutritional and functional quality of human vegetablesFlavonoids are categorised as flavonols, flavones, flavanones, anthocyanins, catechins, and isoflavones based on their chemical structures. They differ in their structure, which affects their bioavailability, antioxidant activity, and biological activity and makes them attractive targets for nutritional and phytochemical studies (Panche et al., 2016).

All vegetable species, cultivars, and plant tissues contain phenolic compounds, though their concentrations and compositions vary greatly. Searches of the most often eaten vegetables have shown large variations in their phenolic composition, which are attributable to genetic, environmental and agronomic factors. Leafy vegetables, root vegetables and fruit vegetables, for instance, may have totally different leaf phenotypes with regard to their nutritional and sensory attributes. Previous profiling studies have shown that there are many different phenolic acids and related compounds in vegetables commonly consumed by a variety of populations, reflecting the complexity of plant phytochemical composition (Huang et al., 2007). Likewise, the extensive studies on leafy vegetables have revealed that polyphenols and flavonoids vary significantly, thus reinforcing the importance of leafy vegetables as a good dietary source of natural antioxidants (Sarker & Oba, 2020).

The scientific literature is ample with health promoting properties of phenolics and flavonoids. These compounds have been known to neutralize Reactive Oxygen Species, thereby reducing the oxidative stress and protecting cellular components from damage. They exhibit antioxidant activity that has been associated with the inhibition of lipid peroxidation, protein oxidation and DNA damage. Furthermore, phenolics have anti-inflammatory properties, regulating pathways associated with inflammatory responses. Experimental and epidemiological data further indicate that dietary flavonoids can play a role in cancer prevention through their effects on cell proliferation, apoptosis and angiogenesis. In addition, these compounds have been shown to be cardioprotective by enhancing endothelial function and preventing oxidative damage in the cardiovascular system. They also have the ability to protect the nervous system and could be used in the prevention of age-related cognitive decrease and neurodegenerative diseases (Cosmulescu et al., 2017).

Analytical chemical techniques have greatly improved to characterize the phenolic and flavonoids compounds in edible vegetables. Numerous phenolic compounds in plant matrices are identified and quantified which have been carried out in detail using conventional chromatographic strategies, especially HPLC-MS. These techniques have been useful to understand the distribution of phenolic acids and flavonoids in a variety of green leafy vegetables (VSVs) and edible plant sources (Kumar, 2017). In more recent times, advanced mass spectrometer platforms have made it possible to obtain detailed phytochemicals profile and its association with antioxidant activities of polyphenol rich fruits and vegetables (Gu et al., 2019).

Alongside the advancements made in chromatography, spectroscopic methods have been developed as rapid, non-destructive and cost-effective methods for phytochemical analysis. The Fourier-transform infrared (FTIR) spectroscopy method has shown great promise in the analysis of phenolic and flavonoid levels from vegetable, with low sample preparation needs. The utility of FTIR spectroscopy in the differentiation of phytochemical compositions in tomato and other vegetable matrices has been successful, emphasizing its application potential in routine screening and quality assessment (Kainat et al., 2022). More recently, FTIR-based methods have also been employed to assess phytochemical profiles and compositional characterization for leafy vegetables, with good results (Diwakar et al., 2025).

The growing interest in functional foods, nutraceutical ingredients, and the need for sound dietary recommendations have highlighted the urgent need for proper profiling of bioactive components in edible vegetables. The need for reliable analytical techniques is crucial for quality control, nutritional assessment, authenticity testing, and value added food product development. Furthermore, comprehensive phenolics and flavonoids characterization can help in breeding programme for improving the nutritional value of vegetable crops. The exploration of various edible plant parts, such as flowers and non-traditional vegetables, has led to the discovery of new and underutilized phytochemical sources that can offer health benefits (Zheng et al., 2019).

The purpose of this review is thus to give detailed information about the phenolics and flavonoids in edible vegetables, focusing especially on the recent advances in the spectroscopic analysis. The appearance and biological importance of these phytochemicals have been discussed, modern spectroscopic methods for their detection and characterization have been evaluated and future trends that are shaping the research in vegetable phytochemistry and food quality assessment have been highlighted.

2. Phenolic and Flavonoid Compounds in Edible Vegetables

One of the most varied classes of phytochemicals present in edible vegetables are phenolic compounds, which are primarily associated with their functional, sensory, and antioxidant qualities. Their production is a result of metabolic pathways in plants and they are important for the protection of plants in case of environmental stress, pathogens and oxidative stress. For easy understanding of the different major classes of phenolic compounds and flavonoids available in edible vegetables, the classes, representative compounds, major vegetable sources, and major biological functions have been summarized in Table 1. The overview emphasizes the structural diversity and functional importance of these phytochemicals that play significant part in nutrition and health promoting roles of vegetable-based diet (Tao et al., 2023; Aryal et al., 2019).

Table 1. Major Classes of Phenolic and Flavonoid Compounds Identified in Edible Vegetables and Their Biological Significance

Class	Subclass/Group	Representative Compounds	Major Vegetable Sources	Major Biological Functions	Reference
Phenolic Compounds	Phenolic Acids (Hydroxybenzoic acids)	Gallic acid, Protocatechuic acid, Vanillic acid, Syringic acid	Leafy vegetables, cruciferous vegetables	Antioxidant activity, oxidative stress protection	Baky et al. (2025)

	Phenolic Acids (Hydroxycinnamic acids)	Caffeic acid, Ferulic acid, p-Coumaric acid, Sinapic acid	Broccoli, cabbage, kale, spinach	Antioxidant and anti-inflammatory activities	Baky et al. (2025)
	Polyphenols	Flavonoids, phenolic glycosides, stilbenes	Conventional and non-conventional edible vegetables	Free radical scavenging, metal chelation, disease prevention	Iqbal et al. (2022)
	Tannins	Hydrolysable tannins, condensed tannins	Leafy vegetables and selected edible plants	Antioxidant, antimicrobial, digestive regulation	Tao et al. (2023)
	Lignans	Secoisolariciresinol, Matairesinol	Various vegetables and edible plants	Cardioprotective, estrogenic, antioxidant effects	Patle et al. (2020)
Flavonoids	Flavonols	Quercetin, Kaempferol, Myricetin	Onion, broccoli, spinach, kale	Antioxidant, anti-inflammatory, cardioprotective	Alam et al. (2020)
	Flavones	Luteolin, Apigenin	Celery, parsley, peppers	Antioxidant, antimicrobial, anti-inflammatory	Aryal et al. (2019)
	Flavanones	Naringenin, Hesperetin	Edible and unconventional vegetables	Antioxidant, antidiabetic, hepatoprotective	Kiani et al. (2023)
	Flavanols (Catechins)	Catechin, Epicatechin	Leafy vegetables and edible plants	Free radical scavenging, antioxidant protection	Alam et al. (2020)
	Anthocyanins	Cyanidin, Delphinidin, Pelargonidin	Red cabbage, beetroot, eggplant	Antioxidant, neuroprotective, cardioprotective	Alam et al. (2020)
	Isoflavones	Genistein, Daidzein	Peas, legumes, soybean-related vegetables	Phytoestrogenic, cardiovascular and bone health support	Kiani et al. (2023)

The information presented in Table 1 demonstrates that edible vegetables contain a wide variety of phenolic and flavonoid compounds with distinct structural characteristics and biological activities.

2.1 Phenolic Compounds' Classification

The primary criteria used to categorise phenolic compounds are their chemical structures and biosynthetic pathways. The primary categories of edible vegetables are lignans, tannins, polyphenols, and phenolic acids. They vary in their molecular structure, solubility and biological activity, and are all involved in antioxidant defense and nutritional value. The use of advanced phytochemical analytical techniques has helped to identify various phenolic compounds in edible plant materials, which will improve understanding in terms of their distribution and functional significance (Patle et al., 2020).

2.1.1 Phenolic Acids: These are one of the most common and simple classes of phenols in vegetables. Generally, they are classified into hydroxybenzoic acids and hydroxycinnamic acids, according to their carbon skeletons. Hydroxybenzoic acids (C6–C1) are often found in leafy vegetables and cruciferous vegetables, such as gallic, protocatechuic, vanillic and syringic acids. Hydroxycinnamic acids include caffeic, ferulic, p-coumaric and sinapic acids with a C6–C3 structure and are frequently found in esterified or conjugated forms. These compounds play a key role in antioxidant activity, flavor enhancement, and protection against oxidative stress. Extensive metabolomic analysis has identified the wide range of phenolic acids in cruciferous vegetables and their significant nutritional and functional value (Baky et al., 2025).

2.1.2 Polyphenols: These are a huge and structurally varied group of compounds containing more than one phenolic ring. Flavonoids, phenolic glycosides, stilbenes and miscellaneous complex derivatives naturally present in vegetables. Polyphenols are known for their ability to bind free radicals, chelate metal ions and regulate cellular signaling pathways implicated in chronic disease prevention. These vary between edible plant species and depend on the post harvest and environmental conditions. The studies on underutilized edible plants, however, have revealed that many plants have significant contents of polyphenols and strong antioxidant activities, suggesting that they can be excellent sources of functional food ingredients (Iqbal et al., 2022).

2.1.3 Tannins: These are polyphenolic compounds with high molecular weight, which are able to bind to proteins, carbohydrates and minerals. They can be broadly categorized into hydrolyзable tannins and condensed tannins (proanthocyanidins). While in many vegetables consumed as food, the amount of tannins is lower compared to fruits, they still play a role in the antioxidant defenses and protection against microbial attack. They possess biological properties such as radical scavenging, anti-inflammatory and digestive modulation. Tannins also affect the sensory properties of the edible vegetables with respect to bitterness and astringency. Modern phytochemical profiling methods have led to a growing documentation of the occurrence of tannin related metabolites, and their nutritional significance and contribution to vegetable quality has been increasing (Tao et al., 2023).

2.1.4 Lignans: Lignans are phenolic dimers which are obtained by the oxidative coupling of phenylpropanoid units. Lignans are another class of phenolics, albeit not as abundant as other classes, but they are now gaining recognition as health-promoting constituents. In the intestine, these compounds are metabolized by gut microbes into enterolignans that can have antioxidant, estrogenic and cardioprotective effects. Lignans have been found in a number of edible vegetables, as part of their phytochemical profile. New spectroscopic and phytochemical studies have allowed characterization of the vegetable matrix containing lignans and have helped to expand the understanding of the structural diversity and biological relevance of these compounds. This type of research is beneficial to the increasing trend of considering lignans as crucial components of the functional value of plant-based nutrition (Patle et al., 2020).

2.2 Classification of Flavonoids

Flavonoids are a prominent class of phenolics with C6–C3–C6 skeleton. Different subclasses are formed by the structural differences within this framework, and each has unique biological activity and health promoting qualities. Edible vegetables have various flavonoids which have antioxidant activity, prevention of diseases and nutritional value (Aryal et al., 2019).

2.2.1 Flavonols: Onions, broccoli, and spinach are just a few of the vegetables that are rich in flavonols, particularly quercetin, kaempferol, and myricetin. These compounds have been found to have potent antioxidant and anti-inflammatory effects and have been linked to the prevention of cardiovascular and metabolic diseases (Alam et al., 2020).

2.2.2 Flavones: Luteolin and apigenin are two flavones that are found in celery, parsley and peppers. They help in plant defense and also exhibit antioxidant, antimicrobial and anti-inflammatory properties, beneficial to human health (Aryal et al., 2019).

2.2.3 Flavanones: Flavanones have a saturated heterocyclic ring; they contain naringenin and hesperetin. These flavonoids are antioxidants, antidiabetic and hepatoprotective and have been found in various edible and unconventional crops (Kiani et al., 2023).

2.2.4 Flavanols (Catechins): Also called flavanols, catechins are compounds that contain catechin and epicatechin. They are known to possess very strong free-radical-scavenging activity, and play a major role in the antioxidant activity of edible vegetables (Alam et al., 2020).

2.2.5 Anthocyanins: They are water-soluble pigments that give red cabbage, eggplant and other vegetables their red, purple and blue hue, which are known as anthocyanins. These compounds have strong antioxidant properties and have been associated with cardioprotective and neuroprotective effects (Alam et al., 2020).

2.2.6 Isoflavones: Legumes and some edible plants are rich sources of isofalvones, particularly genistein and daidzein. They are gaining significant attention for their phytoestrogenic properties, which may be beneficial in cardiovascular health, bone metabolism, and hormone-related disorders (Kiani et al., 2023).

2.3 Major Edible Vegetable Sources

Vegetables are significant food sources of phenolic compounds and flavonoids, however, they have different composition levels in different botanical groups, and some are edible. These bioactive compounds accumulate depending on several factors like species, cultivar, the environmental condition, and cultivation practice. The phenolics and flavonoids found in vegetables are important sources of antioxidants and have several health-promoting effects (Saeed et al., 2019).

Leafy Vegetables: Leafy vegetables are an excellent source of phenolic compounds and flavonoids. Spinach (Spinacia oleracea), lettuce (Lactuca sativa), kale (Brassica oleracea var. acephala) and Amaranthus species are rich in flavonols, phenolic acids and other antioxidant phytochemicals. They are especially noted for their high polyphenols in kale, and glucosinolates in kale, and high antioxidant potential in amaranth. These vegetables are of great value in nutrition and prevention of oxidative stress related disorders (Mateos-Maces et al., 2020; Liu et al., 2021).

Cruciferous Vegetables: Cruciferous vegetables, such as broccoli, cabbage and cauliflower, are particularly rich in a special mix of phenolic compounds, flavonoids and sulfur-containing phytochemicals. Broccoli and kale microgreens have been reported to contain high levels of polyphenols and glucosinolates, which provide the plants with antioxidant and chemoprotective properties. Cruciferous vegetables offer an abundant supply of phytochemicals and have been linked to a decreased risk of chronic diseases with regular consumption (Liu et al., 2021).

Root and Tuber Vegetables: Root and tuber vegetables including carrot, beetroot and radish have nutritional and functional value, with their content of phenolic acids and flavonoids differing. Beetroot is particularly known for its antioxidant pigments and phenolics, with carrots offering phenolics and carotenoids. These vegetables are also significant sources of dietary antioxidants and their bioactive composition has beneficial effect on overall health (Saeed et al., 2019).

Fruit Vegetables: Fruit vegetables, such as tomato, eggplant and bell pepper, are popular foods and have considerable amounts of flavonoids, phenolic acids and other antioxidant compounds. Tomatoes are rich in phenolic metabolites which provide their health benefits while eggplant has chlorogenic acid and anthocyanins. Bell peppers also contain significant amounts of phenolics, which contribute to their antioxidant and nutritional value (Saeed et al., 2019).

Leguminous Vegetables: Leguminous vegetables like green beans and peas are an excellent source of phenolic bioactive compounds, flavonoids, dietary fibers and proteins. The phenolic content is typically lower than that of certain leafy vegetables, but they do make a significant contribution to the total dietary antioxidant intake. Nutritional studies on traditional and less known edible plants have pointed out the nutritional value of legumes as functional foods, with possible health-promoting properties (Hoff et al., 2022).

3. Factors Affecting Phenolic and Flavonoid Content in Vegetables

Several factors contribute to the concentration and composition of the phenolic compounds and flavonoids in vegetable, such as genetic factors, environmental conditions, cultivation practices and post-harvest treatments. All these factors could greatly influence the biosynthesis, accumulation and stability of bioactive compounds and thus the nutritional and functional quality of vegetables. A simplified overview of the key factors that influence the phenolic and flavonoid composition of edible vegetables and how these combined factors influence vegetable quality and functionality is shown in Figure 1.

Figure 1. Determinants of phenolic and flavonoid content in edible vegetables

Phenolic and flavonoid accumulation is a dynamic process as illustrated in Figure 1, and is governed by intrinsic and extrinsic factors. Vegetable crops have genetic potential for the biosynthesis of metabolites, which is affected by environmental conditions and cultivation practices.

3.1 Genetic Factors

Genetic variation is one of the major factors affecting the accumulation of phenolics and flavonoids in vegetables. The regulation of the biosynthesis of these secondary metabolites is regulated by genes of the phenylpropanoid pathway and the expression of these genes can differ significantly between species, cultivars and landraces, leading to significant variation in phytochemical composition. The concentrations of phenolic acids, flavonoids and antioxidant compounds in vegetables of the same species, therefore, may differ significantly. These genetic differences not only affect the amount of bioactive metabolites in edible tissues but also the number of different bioactive metabolites. Increasing attention is being paid to the ability of plant breeding programs to select genotypic traits with improved phytochemical content to boost nutritional quality and health benefits. Comparative studies of onion landraces have shown marked differences in the phenolics present in genetically different onion varieties, suggesting that there is a strong genetic influence on phenolics accumulation. This type of evidence is important because it shows that the genetic background is a fundamental factor in determining the nutritional and functional properties of vegetables, and should be taken into account when developing cultivars with a greater antioxidant potential (Cozzolino et al., 2021).

3.2 Environmental Conditions

Environmental factors have a significant impact on the synthesis and accumulation of phenolic compounds and flavonoids in vegetables. Metabolic activity is strongly affected by temperature and heat or cold stress can induce the synthesis of phenolic metabolites which act as protective agents. Flavonoids are natural photoprotective agents, so the biosynthesis of these compounds is increased by light exposure, especially UV radiation. The accumulation of phytochemicals is also affected by soil parameters such as pH and organic matter as well as mineral availability, which affect the uptake of nutrients and plant metabolism. The availability of water is another factor of paramount importance as moderate drought stress frequently induces the production of antioxidants, as part of the plant's defense against oxidative damage. Within a species of vegetable, the phytochemical composition, therefore, can vary significantly between different environments. The nutritional quality and health-promoting properties of vegetables have been shown to depend on the growing conditions, as changes in the growing conditions can affect both the phenolic profile and antioxidant activities, as revealed by metabolomic analysis (Zheng et al., 2020).

3.3 Agricultural Practices

The phenolic and flavonoids contents in vegetables are strongly affected by the farming practices that influence the growth, stress reaction, and metabolic pathway of the plants. Secondary metabolites are often found in higher concentrations in organic farming systems where the plants are subjected to a higher pressure from natural environmental factors and synthetic chemicals are less used. The application of fertilizers is also important because nutrient availability directly affects the biosynthesis of phenolics and the general metabolism of plants. Imbalanced nutrient management might have a negative effect on phenolic accumulation, while excess nitrogen fertilization might lower accumulation. Another important factor is the stage of harvest since the levels of phenolics and flavonoids change during plant development. For several vegetables, bioactive constituents are at their peak levels of production at certain maturity stages; hence, it is critical to time the harvest for maximum nutritional quality. With edible plants, metabolomics studies have shown that the diversity and amount of generated phytochemicals depend on cultivation practices, and it is important to apply appropriate cultivation strategies to enhance the functional value of vegetable crops (Areche et al., 2020).

3.4 Postharvest Processing

The concentration, stability, and bioavailability of phenolic compounds and flavonoids in vegetables can be greatly impacted by postharvest handling and processing procedures. Enzymatic degradation or oxidation of sensitive phytochemicals may occur as a result of storage conditions, including temperature, humidity, exposure to oxygen and time in storage. The various drying methods such as sun drying, hot-air drying and freeze drying, have varying effects on the retention of phenols depending on the intensity and the duration of the drying process. Phenols might be decreased by thermal degradation, and/or increased by extractability, which can be achieved by cooking methods such as boiling, steaming, frying, and roasting. Fermentation also alters phytochemical composition through microbial changes which result in the formation of new bioactive metabolites and increase in antioxidant activity. Processing-induced changes may have a noteworthy impact on the nutritional quality of vegetables; hence, adequate analytical techniques are needed to monitor the changes. The significance of spectrophotometric and chromatographic methods for comparative evaluation of the phenolics composition in vegetables and the effect of processing vegetable phytochemicals have been highlighted (Khattab et al., 2016).

3.5 Distribution of Phenolics in Plant Parts

The distribution of phenolic compounds in vegetable tissues is not uniform. Due to various physiological processes and metabolic activities, the phytochemical profiles of a plant's leaves, stems, roots, peels, seeds, and edible byproducts can differ. The outer tissues and peels of many vegetables are rich in phenolic compounds, which are likely to be important in protecting the food from the environmental stresses and pathogens. Knowledge of tissue-specific distribution is crucial for effective utilization of vegetable resources and minimizing food processing waste. Recent profiling studies have revealed that several by-products and non-conventional edible plant parts are rich sources of valuable phenolics and flavonoids. The results of such studies could aid in the formulation of sustainable strategies for recovery of bioactive molecules from underutilized vegetable material for inclusion in functional foods, nutraceuticals and value added products. Thus, detailed characterization of phenolic distribution can help not only to improve the nutritional utilization but also economic value of vegetable crops (Abu-Reidah et al., 2017).

4. Sample Preparation and Extraction Strategies

Effective sample preparation and extraction techniques are essential for accurate phenolic compound and flavonoid profiling in edible vegetables. The extraction methods must be suitable in order to obtain maximum recovery and assured analytical results since these phytochemicals have varying polarities, stability and molecular structures. The extraction method can affect the yield of the compounds extracted as well as the results of the spectroscopic and chromatographic analysis that follows. Table 2 provides a comparative overview of the major extraction strategies used for the analysis of vegetable phenolic and flavonoid.

Table 2. Comparison of extraction techniques used for phenolic and flavonoid profiling in edible vegetables

Extraction Method	Principle	Major Advantages	Major Limitations	Typical Applications	Reference
Maceration	Diffusion of phytochemicals into solvent under ambient conditions	Simple, inexpensive, minimal equipment	Long extraction time, high solvent consumption	Preliminary phytochemical screening and laboratory-scale extraction	El-Akad et al. (2021)

Soxhlet Extraction	Continuous solvent reflux and recycling through plant material	Higher extraction efficiency than maceration	Thermal degradation of heat-sensitive compounds, lengthy process	Comprehensive phenolic recovery from dried plant materials	El-Akad et al. (2021)
Ultrasound-Assisted Extraction (UAE)	Acoustic cavitation enhances cell disruption and mass transfer	Reduced extraction time, improved yield, lower solvent use	Possible degradation under excessive sonication	Extraction of phenolics and flavonoids from vegetable tissues	Chen et al. (2021)
Microwave-Assisted Extraction (MAE)	Microwave heating promotes rapid release of intracellular metabolites	Fast extraction, high efficiency, reduced solvent consumption	Potential overheating of thermolabile compounds	Rapid recovery of bioactive phytochemicals	Chen et al. (2021)
Pressurized Liquid Extraction (PLE)	Elevated temperature and pressure improve solvent penetration	High extraction efficiency, shorter processing time	Specialized equipment required	Recovery of bound and free phenolic compounds	Chen et al. (2021)
Supercritical Fluid Extraction (SFE)	Supercritical CO_2 selectively extracts bioactive compounds	Environmentally friendly, minimal solvent residue, high selectivity	High operational cost and equipment complexity	Green extraction of phenolics and antioxidants	Chen et al. (2021)

As shown in Table 2, extraction techniques differ substantially in terms of efficiency, processing time, solvent requirements, and suitability for specific phytochemical classes.

4.1 Conventional Extraction Methods

The traditional methods are still being used for the extraction of the phenolics from the vegetable matrices. Maceration is among the simplest techniques, which involves boiling the plant material in appropriate solvents for longer periods of time to allow the diffusion of active ingredients. This technique is simple and cheap, but may consume large number of solvents and long extraction time. Soxhlet extraction is another traditional method which recycles the solvent continuously through the sample, hence the efficiency of the extraction process is enhanced as compared to simple maceration method. However, prolonged exposure to high temperatures can cause heat-sensitive phenolics and flavonoids to degrade. However, conventional approaches remain useful reference techniques for phytochemical studies and comparative metabolite profiling studies (El-Akad et al., 2021).

4.2 Advanced Extraction Techniques

To get around the drawbacks of traditional extraction techniques, a number of cutting-edge extraction technologies have been created. A shorter extraction time and better yield are achieved, due to the effect of ultrasound-assisted extraction (UAE) on mass transfer by means of acoustic cavitation. Microwave-assisted extraction (MAE) technique is one that employs microwave energy to heat the plant tissues efficiently to release the phytochemicals from the cells. Pressurized liquid extraction (PLE) is the use of high temperature and high pressure to increase solvent penetration and extraction efficacy and to decrease solvent usage. Supercritical fluid extraction (SFE) can be a green and selective method for extraction of bioactive compounds with minimal thermal degradation, especially the supercritical carbon dioxide. These techniques have been getting more and more focus as they offer higher extraction efficiency, lower processing times, and better preservation of antioxidant compounds than the traditional techniques (Chen et al., 2021).

4.3 Factors Influencing Extraction Efficiency

Various parameters such as type of solvent, extraction temperature, extraction time, ratio of the volume of the solvent to the sample, size of the particles and characteristics of the plant matrix affect the efficiency of the extraction of phenolics and flavonoids. The polarity of the solvent is especially relevant as the solubility profile of each phenolic compound is different. The temperature and extraction time should be carefully chosen to achieve an optimum yield of analytes whilst limiting any degradation of thermal labile compounds. Moreover, environmental and physiological conditions which affect the plant material before extraction may alter the availability of the phytochemicals. For soybean microgreens and drought-tolerant leafy vegetables, growth conditions have been shown to influence the content of phenolics and antioxidant capacity, thus influencing the extraction results and analysis results (Zhang et al., 2019; Sarker & Oba, 2020). Thus, the optimization of extraction parameters is crucial to obtain the representative phytochemical profiles and accurate characterization of vegetable bioactive compounds.

5. Spectroscopic Approaches for Phenolic and Flavonoid Profiling

The choice of the right spectroscopic technique is very important for accurate phenols and flavonoids profiling of edible vegetables. The principle of operation, analytical application, sensitivity, portability, and limitations vary with each analytical approach. The knowledge of such characteristics is crucial in the choice of the most appropriate method for qualitative screening, quantitative analysis, metabolomic investigations, and quality assessment. Figure 2 illustrates the comparative overview of the major spectroscopic techniques that are used for phenolic and flavonoid analysis.

Figure 2. Comparative overview of spectroscopic techniques used for phenolic and flavonoid profiling

5.1 Principles of Spectroscopic Analysis

Spectroscopic analysis is based on the interaction between electromagnetic radiation and chemical molecules. If plant extracts or vegetable samples absorb, emit, scatter, or transmit radiation, they give off spectral signals which are linked to their molecular structure and chemical composition. Spectroscopy can be used in phenolic and flavonoid profiling, since these compounds have characteristic spectral responses for their aromatic rings, hydroxyl groups, conjugated double bonds and other functional groups. The main benefits of spectroscopic techniques are speed of analysis, little or no sample preparation, small amount of solvents, non destructive measurement and their suitability for routine quality control. The drawbacks are the interference of spectral bands, the structural specificity is not as high as chromatographic methods and chemometric tools are required for accurate interpretation. Hence, they are often combined with chromatography and mass spectrometry methods to reinforce the quantification and identification of compounds. The significance of employing analytical techniques together for reliable characterization of plant bioactive compounds has been demonstrated by the phytochemical studies using GC-MS and biochemical profiling (Ahmed et al., 2019).

5.2 UV–Visible Spectroscopy

One of the most popular techniques for determining the phenolic and flavonoid contents in advance is UV-visible spectroscopy. It works on the basis of the absorption of ultra-violet (UV) or visible light to the chromophoric groups found in the phenolic structure. UV–Vis is suitable for the quantification of TPC, TFC and antioxidant related assays because of the strong absorption of phenolic acids and flavonoids by means of the presence of conjugated aromatic systems. It is commonly employed in conjunction with colorimetric assays like Folin–Ciocalteu and aluminium chloride assays. The method is quick, inexpensive and simple but lacks specificity, as various substances can absorb light at similar wavelengths. The latest advancements are the integration of UV–Vis data along with multivariate analysis for improved discrimination of plant extracts. Phenols along with flavonoids were also profiled and antioxidant activity was also evaluated in studies conducted on wild Salvia species which further demonstrates the relevance of spectrophotometric approaches in plant phenolic evaluation (Al-Jaber et al., 2020).

5.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR identifies compounds by measuring vibrations in the chemical bonds of molecules. The presence of the functional groups in phenolic and flavonoid compounds like O–H, C=O, C=C, C–O, and aromatic ring structures creates characteristic infrared absorption bands. FTIR is helpful for the rapid fingerprinting of vegetable extracts due to the information it gives on the overall chemical composition with little sample preparation. FTIR can assist in the identification of hydroxyl groups, aromatic skeletal vibrations and glycosidic linkages in phenolic profiling of the flavonoid derivatives. The benefits are that it is fast, has low running costs and is suitable for comparison. But in complex plant matrices, there are also often overlaps of bands, and chemometric interpretation is necessary. FTIR can be used for rapid screening and quality assessment even if the chromatographic technique is more specific for compound level identification. There is a strong focus on molecular level profiling, which can be complemented by functional group identification using FTIR in the studies of separation and structural characterization of flavonoids (Yan et al., 2019).

5.4 Near-Infrared Spectroscopy (NIR)

Near-infrared spectroscopy examines absorption, primarily focusing on overtones and combination vibrations of O–H, C–H, and N–H bonds. NIR is particularly advantageous for the rapid and non-destructive screening of phytochemical composition, moisture, sugars, fibers, and antioxidant-related compounds in vegetables. In general, NIR needs calibration models built by reference analytical methods for phenolic and flavonoid profiling. These models can then be used to quickly predict bioactive compound levels in fresh or minimally processed samples, once validated. The availability of portable NIR instruments has made it a more useful tool for quality assessment in the field and for post harvest monitoring. NIR spectra, however, are broad and complex and chemometric tools are needed for proper interpretation. Its most powerful application is in rapid screening and not in actual structure elucidation. The study of edible medicinal plant flowers demonstrated the need for combining fast profiling technique with compound-specific analysis strategy in the assessment of bioactive plant resources (Zhao et al., 2021).

5.5 Raman Spectroscopy

The principle of Raman spectroscopy is the inelastic scattering of monochromatic light that yields molecular fingerprint data associated with molecular vibration transitions. Useful for identification of phenolic and flavonoid compounds as aromatic rings and systems with multiple conjugations and hydroxylated groups give characteristic Raman signals. Raman is less affected than FTIR by water, so is useful for hydrated vegetable matrices. Surface-Enhanced Raman Spectroscopy (SERS) also enhances sensitivity by enhancing the Raman signals using a metallic nanostructure, which allows the detection of compounds with low abundance in the sample. The use of Raman techniques is growing for food quality analysis, food authentication and quick screening of bioactive compounds. Fluorescence interference and low scattering intensity may, however, hamper performance in complex plant samples. Hence, in many cases, Raman analysis has to be complemented by chemometric methods or reference techniques. The comprehensive polyphenolic profiling by both targeted and untargeted approaches underscores the importance of robust analytical systems that can differentiate structurally similar phenolic metabolites (Oesterle et al., 2024).

5.6 Fluorescence Spectroscopy

Fluorescence spectroscopy is the measurement of light from molecules after they have been excited at certain wavelengths. There are several phenolic compounds and flavonoids that are naturally fluorescent because of their aromatic and conjugated structures. This technique is characterized by high sensitivity, fast analysis and possibility of detection of low content of bioactive compounds in vegetable extracts. It may be used to assess the antioxidant components, track changes during processing, and to fingerprint the plant samples by their fluorescence. But not all phenolics are very fluorescent; moreover, the fluorescence signal can be influenced by pH, solvent, concentration, and matrix effects. Nowadays, the fluorescence spectroscopy techniques are often used in conjunction with multivariate analysis to enhance the selectivity and increase the accuracy of classification. In metabolite analysis of plants, detailed profiling of phenols has demonstrated that fast detection techniques are useful for screening complex plant matrices prior to more detailed chromatographic confirmation (Simirgiotis et al., 2016).

5.7 Nuclear Magnetic Resonance (NMR) Spectroscopy

NMR spectroscopy gives information about the structure of the molecule by detecting the magnetic properties of atomic nuclei, primarily hydrogen and carbon. NMR is particularly useful in phenolic and flavonoid profiling for providing insights into structural characteristics, substitution patterns, glycosylation, and molecular connectivity. NMR is quantitative and in metabolomics, little compound separation is required unlike many other techniques. It is especially used for fingerprinting the complex vegetable extracts and identification of bioactive metabolites, as well as being combined with chromatographic platforms. Quantitative NMR can be used to estimate the abundance of a compound, without the need for heavy external standards. NMR, however, is less sensitive than mass spectrometry, and is expensive to purchase. It has a good role for structural confirmation and metabolomic profiling. The application of analytical fingerprints of metabolites with support from NMR, LC-SPE-NMR, has been illustrated with the case of Ipomoea aquatica, which shows the significance of NMR-supported approach in the identification of bioactive metabolites from edible plant material (Hefny Gad et al., 2018).

5.8 Hyperspectral Imaging (HSI)

Hyperspectral imaging is a combination of spectroscopy and imaging, where chemical and spatial information are obtained from vegetable samples. Hyperspectral images consist of pixels that carry spectral information that can be used to map the distribution of bioactive compounds, pigments, moisture and quality attributes in plant tissues. HSI can be used for non-destructive quality assessment, maturity evaluation, stress detection and classification of vegetable materials for phenolic and flavonoid profiling. It is particularly promising for industrial sorting and real time monitoring without the need of chemical extraction of the samples. But, HSI produces large data volumes and needs high level image processing, calibration and chemometric modeling. The accuracy of its value is dependent on accurate reference data obtained by either chromatographic or spectroscopic techniques. The integration of chemical profiling with fast screening methods for food quality assessment is crucial to be considered in quantitative evaluation of the phenolic profile of plant cultivars using advanced analytical platform (Di Stefano et al., 2017).

6. Chemometric Tools in Spectroscopic Data Analysis

Chemometric analysis is an essential part of phenolic and flavonoid profiling, because of the complexity of the spectroscopic datasets. In the context of phytochemical data acquisition from spectroscopic platforms, chemometric tools can be used to pre-process the data, perform pattern recognition, classification, prediction, and interpretation. Table 3 lists the main chemometric methods for spectroscopic data analysis and their applications in metabolomics of food and plants.

Table 3. Major chemometric tools used in spectroscopic analysis of phenolic and flavonoid compounds

Chemometric Category	Technique	Primary Function	Typical Applications in Phenolic/Flavonoid Profiling	Major Advantage	Reference
Data Pre-processing	Normalization	Corrects intensity variations	Spectral standardization and comparability	Improves data consistency	Hernández et al. (2021)
	Baseline Correction	Removes background drift	FTIR, Raman, and NIR spectral enhancement	Reduces analytical noise	Castagna et al. (2022)
	Smoothing	Reduces random noise	Signal enhancement prior to modelling	Improves signal quality	Hernández et al. (2021)
Multivariate Analysis	Principal Component Analysis (PCA)	Dimensionality reduction	Sample clustering and visualization	Detects hidden patterns	Geana et al. (2023)
	Partial Least Squares Regression (PLSR)	Quantitative prediction	Estimation of phenolic and flavonoid contents	Robust predictive modelling	Salami et al. (2023)
	Linear Discriminant Analysis (LDA)	Supervised classification	Sample discrimination and authentication	High classification accuracy	Mikropoulou et al. (2018)
	Hierarchical Cluster Analysis (HCA)	Similarity assessment	Grouping of vegetable samples	Easy visualization of relationships	Mikropoulou et al. (2018)
Machine Learning Approaches	Support Vector Machine (SVM)	Nonlinear classification	Authentication and quality assessment	High predictive performance	Thovhogi et al. (2023)
	Random Forest (RF)	Ensemble learning	Variable selection and classification	Handles complex datasets	Afifi et al. (2023)
	Artificial Neural Networks (ANN)	Pattern recognition	Prediction of phytochemical traits	Captures nonlinear relationships	Elmosallamy et al. (2021)
	Deep Learning Models	Automated feature extraction	Large-scale spectral interpretation	High accuracy and automation	Afifi et al. (2023)
Metabolomic Integration	Chemometric-Assisted Profiling	Data fusion and biomarker discovery	Metabolomics and phytochemical characterization	Comprehensive biological interpretation	Syabana et al. (2020); Ali et al. (2019)

As summarized in Table 3, chemometric methods play a central role in transforming complex spectroscopic datasets into meaningful biological and analytical information.

6.1 Importance of Chemometrics

Chemometrics is very important for the interpretation of the spectroscopic data obtained in the course of phenolic and flavonoid profiling. Spectroscopic methods generate considerable and complicated data sets with a lot of data overlays from many different phytochemicals, which makes it hard to directly interpret the data. Chemometric methods employ mathematical and statistical algorithms to extract meaningful information, to find pattern, and to enhance classification and prediction accuracy. These methods enable plant samples to be discriminated by their metabolites and biological characteristics. For instance, NMR-based metabolite profiling of vegetables and spices revealed the value of multivariate analysis for establishing correlation between phytochemical composition and biological activity. In the same vein, metabolomics studies of sugarcane juice and molasses involved cutting-edge data processing techniques to decipher intricate phytochemical data and assess biological relevance, further underscoring the significance of chemometrics in plant metabolomics and food analysis (Syabana et al., 2020; Ali et al., 2019).

6.2 Pre-processing Techniques

In chemometric analysis, an important step is pre-processing, which is necessary since raw spectral data often suffer from noise, baseline shifts and scattering effects that can affect the analytical accuracy. Normalization is frequently performed to remove the differences in variations due to different concentrations of samples and instrumental fluctuations. Baseline correction allows for the elimination of unwanted background signals while smoothing methods help to reduce random noises and enhance signal quality. These procedures make the results of the later statistical analysis more reliable and make the model work better. With regard to bioactive substances in lamb's lettuce, there was a need for careful analytical processing in order to assess correctly the differences in bioactive compound content when lamb's lettuce was cultivated under different conditions. Similarly, studies on Salicornia europaea highlighted that environmental and cultivation conditions can affect the phytochemical profile, highlighting the importance of having robust pre-processing methods for reliable spectral interpretation (Hernández et al., 2021; Castagna et al., 2022).

6.3 Multivariate Statistical Methods

Multivariate statistical tools are widely used to interpret spectroscopic data, and identify relationships between samples and variables. Principal Component Analysis (PCA) is used to reduce the amount of data and to visualize clustering patterns between the different vegetable samples. Partial Least Squares Regression (PLSR) is used to build the predictive models between spectral data and reference data, which is used for quantitative estimation of phenolic and flavonoids contents. Linear Discriminant Analysis (LDA) helps in maximizing the intergroup differences of the predefined groups for improving the sample classification, and Hierarchical Cluster Analysis (HCA) arranges the samples based on the similarity and compositional relationship. These are commonly used for food authentication, food quality and metabolomic studies. The capability of PCA and PLSR in complex data sets is well demonstrated on chemometric-assisted discrimination of vegetable oils based on their phenolic and triterpenic profiles. Comparative studies of the polyphenols of rapeseed and edible greens from Greece have also shown the usefulness of clustering and classification analysis for assessing phytochemical diversity and antioxidant activity (Geana et al., 2023; Salami et al., 2023; Mikropoulou et al., 2018).

6.4 Machine Learning and Artificial Intelligence Approaches

Incorporation of machine learning (ML) and artificial intelligence (AI) concepts into the spectroscopic analysis is increasingly growing to enhance the predictive power and to automate the data interpretation. As mentioned, algorithms like Support Vector Machines (SVM), Random Forest (RF), Artificial Neural Networks (ANN), and Deep Learning models are capable of handling high-dimensional datasets and capturing complex nonlinear relationships that might not be detected using traditional statistical methods. These methods are very useful for sample authentication, classification, quality prediction and detection of slight differences in phytochemicals. AI models have shown better performance to process massive metabolomic data and enhance the efficiency of food quality monitoring systems. Traditional vegetables have been studied and revealed significant variations in phenolic and flavonoid contents, which can be gainfully utilized with machine learning based classification approaches. Likewise, studies on Colocasia esculenta and an untargeted metabolomics approach to the phytochemical composition of citrus tissues have underscored the critical importance of sophisticated computational methods in phytochemical characterization and authenticity assessment (Thovhogi et al., 2023; Elmosallamy et al., 2021; Afifi et al., 2023).

7. Recent Developments in Spectroscopic Profiling of Edible Vegetables (2020–2026)

As a result of the recent developments in spectroscopic profiling methods, remarkable advances have been achieved for edible vegetables, specially regarding the need for fast, accurate and non-destructive bioactive compounds assessment. Portable spectroscopic instruments have evolved to a great extent where the phenolic and flavonoids content could be evaluated on site without the necessity of having an extensive laboratory infrastructure. At the same time, non-destructive analytical methods have become more popular as they do not destroy the integrity of the sample and offer good information on the phytochemical content and quality parameters. The characterization of complex phenolic profile in plant derived foods has been significantly improved by high resolution spectroscopic platforms and advanced chromatographic systems, allowing a more accurate chemical fingerprinting and authenticity assessment (Barrientos et al., 2020; Esteban-Munoz et al., 2020). Also, real-time monitoring systems, with spectroscopic sensors, have improved the capability of measuring biochemical changes during cultivation, storage, and processing, which aid in precision agriculture and food quality management. The advent of high throughput screening (HTS) technologies has further enhanced the analysis of phytochemicals, allowing for large number of samples to be analyzed quickly with minimal sample preparation. Simultaneously, the combination of spectroscopy and metabolomics has helped to better understand the diversity and distribution of phenolics in various vegetable species and cultivars. Comparative metabolomic studies have demonstrated significant differences among the flavonoid profiles of plant materials, and there is a great need to integrate spectroscopic and metabolomic techniques for a thorough characterization of plants (Wang et al., 2018). Advanced analytical platforms have also proven to be useful in the identification of bioactive compounds and assessment of their bioactivity in edible plants and food resources in recent years (Silva et al., 2021; Kritsi et al., 2022). Additionally, artificial intelligence and machine-learning algorithms are now being integrated into spectroscopic protocols to facilitate spectral interpretation, automation of spectral classes and enhance predictability in modeling. These AI-driven methods aid in deriving valuable insights from extensive spectral data and can assist in more efficient discrimination of plant matter according to their phytochemical characteristics. This combination of technological advances has shifted phenolic and flavonoid profiling from a laboratory-centric practice to a swift, information-rich, data-driven method for evaluating the nutritional and functional quality of edible vegetables (Zhang et al., 2022).

8. Comparative Evaluation of Spectroscopic Techniques

The choice of a suitable technique for the spectroscopic profiling of phenolic and flavonoids is dependent on the analytical goals, sample type, sensitivity and available resources. UV-Visible spectroscopy is a simple, low cost, less instrumented method and is widely used for the rapid estimation of TPC and TFC. But it gives little information regarding structure and can give interference from overlapping absorption bands. Fourier Transform Infrared (FTIR) spectroscopy can be used for the rapid fingerprinting of functional groups and has the advantage of low requirement for sample preparation, but for the specificity of analysis of complex vegetable matrices may be limited. However, near-Infrared (NIR) spectroscopy is especially promising for non-destructive and high-throughput screening applications and the performance of NIR predictions is largely dependent on calibration models and chemometric analysis. Raman spectroscopy offers detailed molecular information and is relatively unaffected by the presence of water in the sample, but fluorescence interference and relatively weak Raman signals can be a problem in terms of sensitivity. Although fluorescence spectroscopy has been shown to be highly sensitive for naturally fluorescent phenolics, it is not suitable for all phytochemicals. Although Nuclear Magnetic Resonance (NMR) spectroscopy provides highly detailed structural and quantitative information, it is costly to operate and not very sensitive, as compared to mass spectrometry-based approaches. Hyperspectral Imaging (HSI) is an integration of spatial and spectral data, which is especially helpful in assessing phytochemical distribution and quality attributes of intact vegetables.

A critical comparison of those techniques shows that none of them is absolutely the best. Rather, each method has its own pros and cons, depending on the context of the analysis. However, studies on phytochemical characterization of edible plants and plant derived products have shown that in order to characterize all the bioactive compounds, it is necessary to combine several methods of analysis (Basumatary & Narzary, 2017; Mocan et al., 2017). Similarly, the detailed chemical characterization of sea fennel and other matrices has shown that using complementary techniques can increase the likelihood of identifying and characterizing the compounds in the same matrix (Politeo et al., 2023). However, for leafy vegetables and complex plant extracts, more molecular-specific techniques are often favored and for routine quality control and large-scale monitoring programs, rapid screening methods are favored. In addition, the study of phytochemical components of these plants using chromatographic and spectrometric techniques has revealed that depending on the target compounds, the analytical sensitivity, the intended use, and the sample complexity, the choice of method should be carefully considered, to achieve accurate and reliable phenolic and flavonoid profiling (Ayodele et al., 2020).

Table 4. Comparative Evaluation of Spectroscopic Techniques for Phenolic and Flavonoid Profiling

Technique	Sensitivity	Speed	Cost	Sample Preparation	Non-Destructive	Major Applications
UV–Vis Spectroscopy	Moderate	Very High	Low	Minimal	Yes	Total phenolic and flavonoid estimation
FTIR Spectroscopy	Moderate	High	Low–Moderate	Minimal	Yes	Functional group identification and fingerprinting
NIR Spectroscopy	Moderate	Very High	Moderate	Minimal	Yes	Rapid screening and quality assessment
Raman Spectroscopy	High	High	Moderate–High	Minimal	Yes	Molecular fingerprinting and compound identification
Fluorescence Spectroscopy	Very High	High	Moderate	Minimal	Yes	Sensitive detection of fluorescent phenolics
NMR Spectroscopy	Moderate	Moderate	Very High	Moderate	Yes	Structural elucidation and metabolomics
Hyperspectral Imaging (HSI)	High	High	High	Minimal	Yes	Spatial mapping and quality monitoring

9. Challenges and Limitations

Although there is a wide range of developments in the spectroscopic methods of phenolic and flavonoids profiling, these methods still have several limitations which restrain their accuracy and applicability. One of the major problems is the inherent complexity of vegetable matrices, which include a variety of classes of phytochemicals, pigments, carbohydrates, proteins, organic acids and minerals that can interfere with the spectral measurements and compound identification. Furthermore, the spectra of many of these phenolic compounds are such that they overlap since they have similar structural characteristics and absorb or scatter electromagnetic radiation at similar spectral areas, making it difficult to discriminate between them without the use of advanced chemometric tools. Standardization is also a significant hurdle, as different laboratories and studies may have different sample collection and processing methods, instrument configurations, calibration models, and analytical approaches, which can lead to discrepancies in the results. There are also instrumental limitations which impact analytical performance: some spectroscopic methods are not as sensitive for trace level compounds, and other methods require expensive instrumentation, special skills or a lengthy calibration process. In addition, with the advent of high throughput spectroscopic platforms, large and complex datasets are produced which require more advanced statistical/computational methods for interpretation. So, effective data processing, such as noise reduction and feature extraction, multivariate analysis, and model validation, is necessary but may be quite intensive. These analytical problems have been identified during studies involving phytochemical characterization of edible plants, berries, and antioxidant rich botanical materials and it is suggested to incorporate comprehensive chemometric methods along with spectroscopic methods for better reliability, reproducibility, and interpretability of phytochemical analysis results, especially for phenolics and flavonoids profiling (Singh et al., 2021; Sritalahareuthai et al., 2020; Bader Ul Ain et al., 2022).

10. Future Perspectives

Technological advances for faster, portable, sensitive, and data-interpretive analysis of phenolics and flavonoids are expected to propel the future of phenolic and flavonoid profiling in edible vegetables. In the case of vegetable quality, miniaturised spectroscopic sensors are likely to be of growing importance in the monitoring of the material on site and in real time, offering the means for a rapid evaluation of the phytochemical composition in vegetable production and supply chains. The evolution of smartphones based spectroscopy extends the use of analytical technologies by enabling low-cost and easy detection of bioactive compounds in the agricultural and food systems. At the same time, the combination of artificial intelligence (AI) and machine learning (ML) and deep learning algorithms with spectroscopic platforms is likely to enhance the prediction accuracy, automate spectral interpretation, and aid in the identification of complex polyphenols and flavonoids profiles. All these developments will help precision agriculture, which aims to allow farmers to monitor in real-time crop health and environmental stress response, as well as phytochemical accumulation for optimal farming practices and nutritional quality. Furthermore, the use of digital food quality monitoring system based on spectroscopy, cloud computing and Internet of Things (IoT) technologies may enable real-time monitoring of freshness, authenticity and functional properties of vegetables, from the farm to the consumer. It is recommended that future studies should be devoted to the standardization of analytical protocols, extension of spectral libraries, calibration models development and combination of spectroscopic methods with metabolomics and bioinformatics tools. The importance of the interdisciplinary relationship between analytical tools and data-driven approaches for the improvement of knowledge and utilization of bioactive compounds from vegetables has been highlighted in studies where edible plant materials were quantitatively characterized through phytochemical analysis and multivariate analysis was employed to determine variations in phytochemical contents during cultivation (Seal, 2016; Nascimento et al., 2020).

11. CONCLUSION

The phenolic compounds and flavonoids are one of the most important bioactive compounds present in edible vegetables that play a significant role in their nutritional, functional and health-promoting properties. These phytochemicals possess various biological activity and are useful for the healthy diet, such as antioxidant, anti-inflammatory, cardioprotective, anticancer and neuroprotective activity. The phenolics and flavonoids content and composition in vegetable matrices is complex and depends on many factors such as genetic, environmental, agricultural practices, and post-harvest processing. New development of spectroscopic techniques has revolutionized the profiling of such compounds, offering quick, cheap and increasingly non-destructive analytical alternatives to traditional approaches. UV-visible (UV-Vis), FTIR, NIR, Raman spectroscopy, fluorescence spectroscopy, NMR and hyperspectral imaging have shown great promise in qualitative and quantitative analysis of phytochemicals in vegetables. The use of chemometric tools, metabolomics, and artificial intelligence has further improved data interpretation for more accurate classification, authentication, and prediction of phytochemical content. Even though there are challenges with matrix complexity, spectral overlap, standardization and data processing, technological innovations continue to enhance the abilities of spectroscopic analysis. The future perspectives of the profiling of phenolics and flavonoids suggest that future advancements in portable sensors, smartphones-based detection devices, and AI-aided analytical platforms will significantly enhance the efficiency, availability, and applications of these profiling techniques, thereby contributing to improved food quality assessment, precision agriculture, and the development of functional foods.

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