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Extraction Systems and Analytical Techniques for Plant-Derived Phenolic Compounds: A Review

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ABSTRACT: Phenolic compounds, the most abundant secondary metabolites in plants, have gained considerable interest due to their wide-ranging biological activities. Known for their bioactive and antioxidant properties, these natural compounds are highly sought after in the food, cosmetics, chemicals, and pharmaceutical industries. High-quality, phenolic-rich extracts are essential for standardized applications, making efficient extraction techniques and advanced analytical tools indispensable. Recent progress in extraction includes innovative methods like liquid-liquid, solid-liquid, and solid-phase extraction, each contributing to the effective recovery of phenolic compounds. Meanwhile, analytical advancements in techniques such as UV-Visible spectroscopy, infrared analysis and mass spectrometry have enhanced the characterization and quantification of these compounds. This review presents a detailed overview of plant-derived phenolic compounds, covering their classification, extraction techniques, analytical approaches, and potential applications. By consolidating current knowledge, it seeks to provide insights into the development of phenolic-based products and guide future research. Key areas for ongoing investigation include optimizing extraction techniques, understanding the biological mechanisms underlying phenolic activities, and exploring applications in human health and sustainable industries. Ultimately, this work highlights both the opportunities and challenges in advancing phenolic research and applications across multiple fields.

KEYWORDS: Phenolic compounds, extraction techniques, analytical approaches, bioactive compounds, spectroscopy.

I. INTRODUCTION

Phenolic compounds are a diverse group of secondary metabolites found in plants, widely distributed across various plant organs such as fruits, vegetables, grains, legumes, spices, and nuts. These compounds play crucial roles in plant processes like coloring, quality, and stress resistance. In addition to their function in plants, phenolic compounds offer significant health benefits to humans, exhibiting natural antioxidant, anti-microbial, anticancer, and anti-inflammatory properties. Chemically, phenolic compounds share a common structure characterized by an aromatic ring with one or more hydroxyl groups. They can be classified into several categories, including flavonoids, phenolic acids, tannins, stilbenes, and lignans. Some phenolic acids are monophenolic, while others are polyphenolic. These compounds are present not only in fresh plant foods but also in food by-products from their processing. The chemical composition of a plant product, including its phenolic content, can be determined through qualitative analysis and is influenced by the choice of solvent used for extraction. Phenolic compounds are highly complex and structurally diverse, with many yet to be fully identified [1]. Beyond their roles in enhancing color and taste, these compounds are studied for their potential health-promoting properties. By acting as antioxidants, they help neutralize harmful reactive oxygen and nitrogen species generated during metabolism, potentially preventing various diseases [2]. The health benefits of phenolic compounds underscore their importance in nutrition, highlighting their role in preventing disease exacerbated by poor dietary habits. All these methods are used to estimate the total phenolic content, are not selective for single compounds, and suffer from matrix effects, interfering compounds, and difficulties due to the pH and solubility differences. The current level of knowledge about the biochemical effects of dietary polyphenols and their involvement in human health and diseases is discussed in this study [3]. Therefore, the aim of this article is to collect some of the most recent literature on the characterization and analysis technique, as well as on the extraction methods focusing on the more novel and emerging technologies used for

the recovery of these high added value compounds. The main biological activities of some important phenolic compounds are also demonstrated. Phenolic compounds, including polyphenols, are gaining significant attention in both scientific research and health applications due to their wide range of biological activities. These compounds are widely distributed in plants, and can also be found in cereals, dried legumes, chocolate, and other food sources. Phenolic and polyphenolic compounds are recognized for their antioxidant properties, which help protect human tissues from oxidative stress and associated damage [4]. In addition to their antioxidant functions, phenolic compounds play a critical role in regulating various metabolic functions in plants, including growth, pigmentation, and resistance to pathogens. Phenolic compounds have diverse chemical structures, ranging from simple molecules to complex polymeric forms, and their biological activity is closely linked to these structures [5]. Many studies suggest that increased consumption of foods rich in phenolic compounds may reduce the risk of chronic diseases, including cancer and heart disease [6]. This has led to a growing interest in the potential of phenolic compounds for health promotion and disease prevention. Several analytical methods are commonly used to assess the phenolic content of food and plant materials. The composition of phenolic compounds in raw materials can vary based on factors such as plant species, cultivation conditions, and processing methods [7]. Understanding the phenolic profiles of different natural sources is essential for developing reliable and efficient extraction and quantification methods. These methods typically rely on spectrophotometric techniques for global estimation of phenolic content. Due to their cost-effectiveness, accessibility, and wide availability, phenolic compounds are increasingly explored for their therapeutic potential, particularly in diet-based health strategies. They have garnered special attention for their anti-inflammatory properties and their ability to influence various human diseases. The growing body of research into the biological activities of phenolic compounds is paving the way for further exploration into their use for health maintenance and disease prevention [8]. Research into the classification of natural polyphenols and the development of various extraction procedures continues to be an important area of study. Moving forward, there is a need for rapid, sensitive, and reliable analytical methods to assess the quantity and quality of these bioactive compounds from a variety of natural sources.

II. METHOD OF EXTRACTING PHENOLIC COMPOUNDS

Solid-Liquid Extraction (SLE) – It is one of the simplest and most common methods for extracting phenolic compounds from various plants. This process involves directly extracting fresh or freeze-dried plant material using different solvents, such as methanol, ethanol, acetone, or aqueous mixtures. After extraction, additional steps, like column chromatography or solid-phase extraction, are often necessary to eliminate unwanted substances. Research indicates that the choice of solvent can significantly impact extraction efficiency. For example, acetone has proven to be particularly effective for extracting polyphenols from lychee flowers, outperforming methanol, ethanol, and water. Additionally, Medina-Medrano et al. found that a solvent combination of ethanol and water can greatly enhance the phenolic content extracted from the leaves of *Stevia Origanoides*, *Stevia ovate*, and *Stevia viscida*. While SLE is straightforward and easy to operate, it has some drawbacks, including lengthy extraction times, lower efficiency, and a higher dependence on potentially hazardous organic solvents [1&9]. These limitations can affect its practicality and safety in larger-scale applications.

Ultrasound-Assisted Extraction (UAE) – It is an efficient extraction technique that offers several advantages over conventional methods. Key benefits of UAE include lower instrumental requirements, ease of operation, reduced extraction times, decreased solvent consumption, and lower temperatures. In UAE, high-frequency sound waves, typically between 20 kHz and 40 kHz, are employed to facilitate the release of phenolic compounds from plant materials. The effectiveness of the process is influenced not only by the sonication itself but also by the properties of the solvent and the sample. By reducing the particle size of the plant material, UAE increases the surface area exposed to the solvent and enhances cavitation, which further improves extraction efficiency [2&9]. This method is cost-effective and requires minimal equipment. Important parameters that affect the application of UAE include extraction time, temperature, amplitude, and sonication power.

Supercritical Fluid Extraction (SFE) – It is a technique based on the principle that the solubility of a substance is significantly influenced by the density of the solvent. A key feature of SFE is the ability to modify the density of the solvent by adjusting temperature or pressure, making it particularly effective for recovering nonpolar phenolic compounds. SFE is an eco-friendly and sustainable method for obtaining phenolic extracts from plant materials. Common solvents used in this technique include supercritical carbon dioxide (CO₂), ethane, butane, pentane, nitrous oxide, ammonia, and water. This method often requires less toxic organic reagents, making it a safer alternative. SFE has been

successfully applied to extract phenolic compounds, anthocyanins, and flavonoids from sources such as purple corn cob and peach leaves. The resulting extracts have valuable applications in food, feed, and medicinal products [9].

Microwave-Assisted Extraction (MAE) – It is an innovative technique developed for the efficient extraction of phenolic compounds. This method relies on the characteristics of the plant matrix and the specific solvents used. MAE utilizes high-frequency radiation in the form of electromagnetic waves, with wavelengths ranging from 1 nm to 30 cm. Key parameters that influence MAE include the choice of solvent, temperature, microwave power, irradiation time, and the properties of the plant material. The advantages of MAE are numerous, including reduced operation time, lower solvent consumption, decreased production costs, and high extraction yields. This makes it an effective and cost-efficient option for obtaining phenolic compounds from various sources.

Liquid-Liquid Extraction (LLE) – It is a crucial method for extracting phenolic compounds, where the solubility of these compounds in the solvent significantly influences the extraction process. Key factors affecting LLE include miscibility, density, pH, temperature, extraction time, and the number of successive extractions. Typically, the extraction of phenolic compounds from plant materials begins with solid-liquid extraction, followed by liquid-liquid extraction of the resulting aqueous extract. Aqueous Two-Phase Extraction (ATPE) utilizes liquid-liquid biphasic systems formed by combining hydrophilic substances, such as polymers and alcohols [2&10]. After mixing, the solution is centrifuged to separate the organic and aqueous layers, allowing for the effective isolation of the desired phenolic compounds.

Pressurized Liquid Extraction (PLE) – It is also known as Accelerated Solvent Extraction, is an efficient solid-liquid extraction method performed in an automated system at elevated temperatures (up to 200 °C) and pressures (around 1700 psi). This technique allows for the rapid extraction of compounds within a short timeframe. The use of high temperatures decreases solvent viscosity and helps break solute-matrix interactions, such as dipole-dipole attractions, hydrogen bonds, and Van der Waals forces. However, one disadvantage of PLE in food applications is the potential extraction of undesirable compounds. Despite this, PLE has proven effective for extracting phenolic compounds, flavonoids, and catechins from various plant materials, including olive leaves and avocado peel by-products.

Solid-Phase Extraction (SPE) – SPE is an important step for purifying crude plant extracts by removing interferences. In this process, phenolic compounds are adsorbed onto a column packed with functionalized materials. One of the main advantages of SPE is its compatibility with High-Performance Liquid Chromatography (HPLC), allowing for an inline combination of extraction and analysis. Various solid-phase sorbents can be used based on their selectivity and stability. There are two main variants of SPE: dispersive solid-phase extraction and magnetic solid-phase extraction, each offering unique benefits for specific applications [10].

III. CHEMICAL METHODS

Alkali Method of Extraction-

The alkali method utilizes alkalis like sodium hydroxide (NaOH) to facilitate the extraction process. This approach cleaves ester bonds, releasing polyphenols that are typically trapped within cell wall components. Bound phenolic compounds such as chlorogenic acid, caffeic acid, p-coumaric acid, ferulic acid, syringic acid, and vanillic acid can be effectively extracted using this technique. Additionally, the inclusion of ascorbic acid and ethylenedinitriolotriacetic acid (EDTA) is recommended to prevent the oxidation of bioactive compounds. For optimal results, this method should be carried out in an inert gas atmosphere and in darkness. It is important to note that a significant portion of protein becomes insoluble during the process, leading to protein precipitation under strongly basic conditions.

Acidic Method of Extraction- The acidic method is another widely used chemical approach for extracting phenolic compounds. It typically employs strong acids to facilitate the extraction of certain phenolics. This method is often regarded as more reliable and efficient than the alkali method. However, it does have some drawbacks, including the need for elevated temperatures, which can denature some phenolic compounds. Acid hydrolysis plays a key role in breaking the ester and glycosidic bonds between polyphenols and cell wall components, enabling effective extraction.

Biological Method of Extraction- The biological method utilizes biological entities, such as enzymes, for the extraction of compounds. This enzymatic approach is more specific, effective, and reliable compared to chemical methods. For example, the enzyme ferulic acid esterase is employed to disrupt the interactions between ferulic acid and oligosaccharide

components, enhancing extraction efficiency. This method effectively addresses the limit chemicals methods. Additionally, carbohydrate-hydrolyzing enzymes such as pectinase, amylase, xylanase, and cellulose can be utilized to extract bioactive phenolic compounds (BPs) more effectively.

Physical Method of Extraction- The physical method of extraction is highly cost-effective compared to other extraction techniques and is widely used at the industrial level. This method employs elevated heat treatment, microwave irradiation, ultrasound, and ultra-high pressure to disrupt covalent, hydrophobic, and hydrogen bonds between phenolic compounds and macromolecules. These processes enhance the extraction efficiency and yield of bioactive phenolic compounds [5&11].

IV. ANALYTICAL TECHNIQUE FOR PHENOLIC COMPOUNDS

UV-Visible Spectroscopy- UV-Visible spectroscopy is a powerful tool for identifying the structural classes of phenolic compounds by analyzing their absorption spectra within the 190 to 600 nm range. The UV spectra can be influenced by various functional groups that introduce new absorption bands. Substitutions on the aromatic ring can modify both the molar absorptivity and the wavelengths of maximum absorption for different compounds. For instance, bands at 305-390 nm (Band 1 or B) are associated with the cinnamoyl structure found in flavonoids, while bands at 230-300 nm (Band 11 or A) relate to the benzene or benzoyl moieties. Phenolic compounds are categorized into main groups, such as cinnamic acid derivatives, hydroxybenzoic acids, and tyrosol derivatives. To accurately identify unknown compounds, comparison with standards is essential, focusing on both retention times and UV-Visible spectra.

Fluorescence Spectroscopy- Fluorescence spectroscopy capitalizes on the fluorescence properties of phenolic compounds, which often feature aromatic rings and conjugated π bonds. For instance, an excitation wavelength of 280 nm has been utilized to detect phenolic compounds in wines, with emission spectra recorded from 295 to 600 nm. This technique enables wine classification based on their phenolic content and utilizes multivariate analyses, such as factor analysis. Coupling fluorescence with separation methods enhances sensitivity and selectivity, making it superior to UV-Vis techniques for detecting over 20 phenolic compounds, particularly flavonol oligomers, as it relates to their degree of polymerization and galloyl units [12].

Infrared Spectroscopy- Infrared (IR) spectroscopy spans wavelengths from 700 nm to 1 nm and is categorized into near-IR (NIR), mid-IR, and far-IR regions. Compounds that absorb infrared light yield characteristic IR spectra, making this technique useful for profiling phenolic compounds in various matrices, including olive oil and fruits. NIR offers advantages such as rapid, non-destructive analysis, though it can suffer from spectral overlap that complicates interpretation. Fourier transform IR spectroscopy can be employed in mid-IR for detailed functional group analysis, and NIR has been used for adulteration detection. Recent advancements in combining IR with liquid chromatography (LC) present new opportunities, although studies specifically targeting phenolic compounds remain limited [13].

Mass Spectrometry- Mass spectrometry (MS) is crucial for elucidating and profiling the structures of phenolic compounds. Various types of mass spectrometers, classified into low- and high-resolution categories, provide high sensitivity and rapid analysis. Low-resolution MS, particularly when coupled with liquid chromatography (LC), is cost-effective for identifying compounds using databases. High-resolution MS, with advanced software, facilitates the determination of molecular formulas based on isotopic patterns and accurate mass measurements. Techniques like LC-QQQ are often used for targeted phenolic analyses, while innovative methods such as ambient MS allow for detailed profiling with mass errors below 1 ppm. Despite its advantages, isomeric compounds can be challenging to distinguish using these methods.

Nuclear Magnetic Resonance Spectroscopy- Nuclear magnetic resonance (NMR) spectroscopy is vital for determining the chemical structures of isolated phenolic compounds. Various 2D NMR experiments, such as COSY and NOESY, help in analyzing complex mixtures found in food samples. While NMR offers lower sensitivity compared to other methods, it doesn't require chemical derivatization, and high-resolution multinuclear NMR can quantify phenolic compounds effectively. Coupling NMR with bioassays allows for the screening of active molecules, while integration with LC and solid-phase extraction (SPE) enhances the analysis of enriched samples [14].

Spectrophotometry- Spectrophotometry is a straightforward, rapid technique for quantifying phenolic compounds in plant materials. The Folin-Ciocalteu assay, a modification of the Folin-Denis method, is widely used to detect total phenolic content [1&14]. The procedure involves extracting phenolic compounds, reacting them with the reagent, and measuring absorbance. This technique effectively quantifies flavonoids and condensed tannins, making it a common choice for assessing different classes of phenolic compounds due to its simplicity and cost-effectiveness.

Gas Chromatography- Gas chromatography (GC) is employed for the separation, identification, and quantification of certain phenolic compounds, such as tannins and flavonoids. This method relies on the volatility and specific evaporation temperatures of compounds as they pass through a heated column. GC coupled with mass spectrometry (GC-MS) has gained popularity for analyzing complex samples due to its sensitivity and selectivity. The use of capillary columns and helium as a carrier gas enhances the separation process, enabling detailed characterization of compounds like lignans in plant extracts.

High-Pressure Liquid Chromatography- High-pressure liquid chromatography (HPLC) is the preferred method for separating and detecting phenolic compounds, offering advantages such as high sensitivity, selectivity, and precision. HPLC operates by separating compounds based on their solubility and interactions within a less polar mobile phase. While some phenolic classes, particularly flavonoid glycosides, may lack standards, HPLC remains a valuable analytical tool for phenolic identification through retention time comparison with known standards.

HPLC-Mass Spectrometry- HPLC combined with mass spectrometry (MS) offers a sophisticated approach for analyzing phenolic compounds, providing detailed structural information from crude or partially purified samples. This method boasts high sensitivity and selectivity, making it the go-to technique for phenolic compound analysis. Despite the higher costs associated with MS, its capability to deliver comprehensive structural data from diverse biological resources positions it as an essential tool in phenolic research.

HPLC-Diode Array Detection- HPLC with diode array detection (HPLC-DAD) is a common and effective method for analyzing phenolic compounds in plants. The DAD can scan the entire UV-Vis spectrum, offering critical spectral information for compound identification. Compared to other detection methods, HPLC-DAD is considered simpler, cost-effective, and reliable, providing a robust platform for food composition analysis.

HPLC-Fluorescence Detection- HPLC-fluorescence detection is used for analyzing phenolic compounds that either naturally fluoresce or can be derivatized to become fluorescent. Thin-layer chromatography (TLC) offers a low-cost alternative for separating and detecting multiple phenolic substances simultaneously on a single plate. Additionally, advanced techniques like ultra-HPLC-electrospray ionization-tandem MS have recently been developed for the sensitive and selective determination of phenolic acids and flavonoids across various plant species, enhancing the capability for comprehensive analysis [1&15].

V. HEALTH BENEFITS IN PHENOLICS

Antimicrobial Activity- Microbial pathogens often spread infections through quorum sensing, a density-dependent communication method that facilitates biofilm formation, antibiotic resistance, sporulation, and the expression of virulence genes. This behavior is particularly concerning in the food industry due to its potential for serious contamination. Various polyphenols exhibit different mechanisms of action; for instance, flavonoids and catechins can penetrate bacterial cell lipid bilayers, leading to the release of intracellular components and subsequent cell death. These compounds effectively suppress bacterial adhesion, biofilm formation, motility, and toxin release, demonstrating significant antimicrobial activity that can be harnessed for natural food additives and preservatives [9&16]. Additionally, the total phenolic content in spices contributes to their antimicrobial properties, enhancing the survival of beneficial probiotic bacteria.

Antioxidant Activity- Oxidative stress is a major contributor to numerous chronic diseases, making the use of natural antioxidants essential for neutralizing free radicals. Recent studies have evaluated the antioxidant efficacy of 12 commonly used spices—such as clove, cinnamon, and turmeric—by analyzing their total phenolic content. Polyphenols can inhibit xanthine oxidase, an enzyme involved in superoxide ion production, and their antioxidant power is influenced by the number and positioning of hydroxyl groups within their structure. Compounds like hydroxycinnamic acid, ferulic

acid, coumaric acid, and syringic acid also demonstrate significant radical scavenging activity. These phenolic compounds stabilize free radicals by donating hydrogen atoms, thereby reducing mitochondrial reactive oxygen species (ROS) generation [16].

Anti-Inflammatory Activity- Inflammation is often linked to elevated nitric oxide (NO) production and oxidative imbalance. Polyphenols can down regulate pro-inflammatory enzymes, measured through their effects on NO and TNF synthesis, especially in response to lipopolysaccharide (LPS) exposure. NO plays a pivotal role in inflammation, and polyphenols can modulate its production. This regulation impacts various inflammatory signaling pathways, including those involving nucleotide-binding oligomerization domain and NLRP3 signaling, which are crucial in triggering inflammatory responses [11&16]. Studies show that many spices significantly inhibit NO and TNF synthesis, attributed to their polyphenol content.

Anticancer Activity- Cancer, a complex and lethal disorder characterized by uncontrolled cell proliferation, is projected to cause over 22 million deaths by 2030. Polyphenols are believed to interrupt multiple stages of cancer progression, including cell proliferation, inflammation, apoptosis, and metastasis. Their antioxidant properties play a critical role in preventing carcinogenesis, as oxidative stress is a key factor in cancer development. Research on the antineoplastic effects of methanolic extracts from 15 spices shows that those with higher polyphenol content exhibit better anticancer activity [12&16]. These compounds can activate phase I enzymes that mitigate oxidative stress and aid in cancer prevention by neutralizing free radicals.

Anti-Cardiovascular Activity- The dysregulation of the endothelium is a key factor in the development of atherothrombosis and cardiovascular disease, contributing to platelet hyperactivation and the formation of thrombi. Several risk factors, including age, high cholesterol (HC), high blood pressure (HBP), LDL oxidation, inflammation, hyperglycemia, and elevated urinary isoprostanes, all contribute to cardiometabolic health impairment. These factors promote the oxidation of low-density lipoprotein (LDL), a key event in the progression of atherosclerosis, while also facilitating platelet aggregation—a crucial mechanism in the development of cardiovascular disease. Research suggests that a diet rich in phenolic compounds may reduce the risk of coronary heart disease by inhibiting LDL oxidation and reducing platelet aggregation. Phenolic compounds can modulate several risk factors associated with cardiovascular disease by decreasing pro-inflammatory markers, reducing oxidative stress, and promoting apoptosis in damaged cells. In addition, polyphenols may improve the composition of the gut microbiota, which represents an advanced strategy for addressing cardiovascular conditions. This modulation of risk factors, in turn, may help mitigate not only cardiovascular diseases but also neurological and cerebrovascular disorders [16].

Hypertension- Hypertension is a prevalent condition associated with an increased risk of cardiovascular disease, affecting up to one-quarter of the global adult population. Angiotensin-converting enzyme (ACE) inhibitors are commonly used to treat hypertension by converting angiotensin I to the vasoconstrictive peptide angiotensin II while degrading bradykinin, a vasodilator. While conventional ACE inhibitors like captopril and enalapril have known side effects, natural ACE inhibitors from plant sources have shown promise [4&17]. For instance, cocoa polyphenols are bioavailable and exhibit antihypertensive effects through ACE inhibition. Recent studies have identified 74 plant families with significant ACE inhibitory actions, highlighting the potential of natural compounds in managing hypertension. Certainly! Here's a summary of the information you've provided on various health conditions and the potential roles of natural compounds.

Type 2 Diabetes Mellitus- *Bergenia ciliate* contains active compounds like galloyllecatechin and galloylcatechin, which inhibit key enzymes such as porcine pancreatic delay glucose absorption, showing promise as a treatment for Type 2 diabetes mellitus (T2DM). Other natural substances, including flavonoids and non-flavonoids, are suggested as safe alternatives to traditional medications and may help prevent complications associated with T2DM by supporting pancreatic function.

Skin Cancer- Skin tumors, particularly melanoma, pose significant health risks. While melanoma is less common than basal and squamous cell carcinomas, its incidence is rising, especially among Caucasians. Natural compounds, including phenolic compounds and curcumin, have shown potential in inhibiting cancer cell growth. The chemopreventive effects of polyphenols like anthocyanins and EGCG are being explored for their ability to combat melanoma [17].

Alzheimer Disease-

Alzheimer's disease (AD) is a complex neurodegenerative condition characterized by reduced acetylcholine levels due to the activity of enzymes like acetylcholinesterase (AChE) and butyrylcholinesterase (BChE). Inhibiting these enzymes may enhance acetylcholine availability and reduce amyloid-beta accumulation, both critical in AD pathology. Polyphenols have potential as therapeutic agents, although their exact mechanisms remain under investigation.

Psoriasis- Psoriasis is a hereditary condition marked by skin inflammation and abnormal keratinocyte growth. Treatments focus on reducing keratinocyte proliferation and inflammation. Natural compounds, particularly polyphenols, exhibit immunosuppressive properties that may help manage psoriasis symptoms. Evidence suggests that dietary factors can influence the course of the disease [18].

Acne Vulgaris- Propionibacterium acnes are a key player in acne, and treatments often include antimicrobial agents like benzoyl peroxide. Natural extracts, such as those from eucalyptus and wild watermelon, contain phenolic compounds with antibacterial properties, providing alternative options for managing acne.

Antibacterial and Antiviral Activities- Plant-derived phenolic compounds, such as catechins from green tea, demonstrate antimicrobial properties. Honey also exhibits antibacterial effects [18&19]. Emerging research on biopolymers as carriers for antiviral compounds is promising, with substances like green tea extract showing potential in food industry applications.

Anti-Aging Effects- Aging is linked to oxidative stress and free radical accumulation. Antioxidant-rich foods, particularly those high in polyphenols like anthocyanins, may combat aging by reducing inflammation and oxidative damage. Green tea catechins have shown anti-aging benefits, and polyphenols are recognized for their neuroprotective effects, highlighting their importance in age-related health [20]. This overview highlights the therapeutic potential of natural compounds across various health conditions, suggesting their integration into preventative and treatment strategies.

VI. DISCUSSION

The detection of plant phenolic compounds plays a key role in understanding their health benefits, such as antioxidant and anti-inflammatory properties. Several analytical techniques are widely used for this purpose, each with its strengths and limitations. HPLC, especially when paired with UV-Vis or MS detectors, is one of the most popular methods due to its high accuracy and ability to analyze complex mixtures of phenolic compounds. GC-MS is also effective, particularly for volatile phenolics, though it requires chemical modification of the compounds before analysis. Newer methods, such as the CoulArray electrochemical detector, are gaining attention for their sensitivity and lower cost, offering a good alternative for detecting antioxidant phenolic compounds when paired with HPLC. Techniques like CE offer high-resolution separations, while FTIR is useful for identifying functional groups in phenolic compounds, though it's less effective for precise quantification. Despite these advances, challenges such as interference from the sample matrix still exist. However, the use of Artificial Intelligence (AI) and Machine Learning (ML) shows great potential in improving detection accuracy and processing large datasets more efficiently. As these technologies continue to develop, they could greatly enhance the analysis of phenolic compounds in plant samples

VII. CONCLUSION

The detection and analysis of plant phenolic compounds rely on a diverse array of analytical techniques, each offering unique advantages in terms of sensitivity, specificity, and application. Techniques like High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), and Mass Spectrometry (MS) are invaluable for separating, quantifying, and characterizing phenolic compounds, providing both qualitative and quantitative insights. UV-Visible Spectroscopy (UV-Vis) and Electrochemical Methods offer rapid and cost-effective alternatives for the detection of phenolic compounds, especially in complex matrices. Capillary Electrophoresis (CE) and Fourier Transform Infrared Spectroscopy (FTIR) offer complementary capabilities, providing high-resolution separation and functional group identification, respectively. For structural elucidation, Nuclear Magnetic Resonance (NMR) Spectroscopy remains a powerful tool, although it is typically reserved for more detailed analysis. The CoulArray detector, with its high selectivity and sensitivity, stands out for its ability to identify electroactive phenolic compounds in food matrices, offering a green

and efficient approach to phenolic compound detection. These analytical methods, when used in combination, enable comprehensive profiling of phenolic compounds, supporting applications in food quality control, medicinal research, and plant-based health products. Future studies should continue exploring new methods for improved identification and characterization, especially in less explored plant sources like cereals, vegetables, and fruits. Together, these advancements contribute to a deeper understanding of phenolic compounds' roles and applications in various fields.

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Abbreviation

Solid Liquid Extraction [SLE].

Ultrasound Assisted Extraction [USE].

Supercritical Fluid Extraction [SFE].

Microwave Assisted Extraction [MAE].

Liquid-liquid Extraction [LLE].
Pressurized Liquid Extraction [PLE].
Solid Phase Extraction [SPE].
UV-Visible Spectroscopy [UV-VIS].
Infrared Spectroscopy [IR].
Mass Spectroscopy [MS].
Nuclear magnetic Resonance Spectroscopy [NMR].
Gas chromatography [GC].
High Pressure Liquid Chromatography [HPLC].
HPLC-Diode Array Detection [HPLC-DAD].
Thin layer chromatography [TLC].
Reactive Oxygen Species [ROS].
Nitric Oxide [NO].
Lipopolysaccharide [LPS].
High Cholesterol [HC].
High Blood Pressure [HBP].
Low Density Lipoprotein [LDL].
Angiotensin Converting Enzymes [ACE].
Type 2 Diabetes Mellitus [T2DM].
Alzheimer Disease [AD].
Acetyl cholinesterase [ACHE].
Butyrylcholinesterase [BCHE].



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