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Structural and Functional Properties of Polyphenol Complexes: Polyphenol-Protein Complexes and Polyphenol- Starch Complexes

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Abstract: Polyphenols are natural compounds originate in various vegetables, fruits, herbs, and grains, and they have increased scientific attention because of their powerful effects on human health. They support our bodies by reducing oxidative inflammation and stress. which are common causes of chronic diseases such as diabetes, heart problems and neurodegenerative disorders. Interestingly, under certain conditions, polyphenols can also act in the opposite way, creating stress precisely inside harmful or cancerous cells. This unique dual behaviour makes them promising candidates for future therapeutic applications. However, polyphenols often disruption rapidly and are not permanently absorbed by the body. To address this, researchers are modified with new way to combine polyphenols with starches and proteins. These mixtures help retain the polyphenols stable, make them more active during digestion, and permit to release gradually where they are needed. Such combination is also showing great promise in refining increasing shelf life, food quality, and making healthier functional foods.

To create of these valued compounds in an extra sustainable way, modern green extraction techniques, such as pressurized supercritical fluid extraction, liquid extraction, ultrasound methods, and heat-assisted processing, are helping to recover high-quality polyphenols without harming the environment. Many of these methods also use agricultural by-products, turning waste into useful resources. Overall, polyphenols represent an opportunity to developed healthier foods, safer packaging, and even more advanced biomedical materials. With continued research, they may play a major role in shaping future innovations that support both human well-being and environmental sustainability.

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I. INTRODUCTION

Polyphenols compound are natural compounds found in many plants, renowned intended for their health benefits as their antioxidant properties. They can act in two opposite ways: first is works antioxidants agent, they protect our cells and tissues from damage caused by unstable molecules called free radicals in our body, which are linked to many problems like heart disease, diabetes, cancer, and brain sicknesses etc. But in some cases, they can also act as pro-oxidants agent,[1], [2] creating reactive molecules that can harm harmful cells, especially useful when targeting cancer cells and its use brain disease[3].

Today, researchers are to study about greener, harmless habits to get polyphenols from plants. One example is using natural deep assortment solvents (NADES), which are eco-friendly liquids that pull out more of the beneficial compounds while keeping them active. These methods avoid harmful chemicals, making them safer for people and the planet[4] [5].

Polyphenols can also join with proteins in food or the body by making polyphenol-complex, which can make them more stable, easier for the body to use, and sometimes even more effective the other phenolic compound. This makes them useful not only in medicine. But also in food preservation, packaging, and health supplements by its oxidant properties[6].

By understanding and using both their protective (antioxidant) and targeted-attack (pro-oxidant) effects, researchers hope to create new treatments that prevent disease, fight inflammation, and even kill harmful cells, while using supportable approaches to produce them.

To bond this gap, researchers are turning to hydrogels, soft, water-rich materials that feel more like living tissue and cells. By adding special natural compounds called polyphenols, found in plants like olives, tea, and grapes, researchers can make these hydrogels stick better to skin or internal tissues, stay stable inside the body, and even help reduce inflammation. Polyphenols are famous for their antioxidant powers as well as pro-oxidant powers, which help

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protect cells from damage caused by unstable molecules called free radicals. In olive oil, for example, compounds like oleuropein and hydrogels have been shown to fight oxidative stress, calm inflammation, and even protect the brain and tissues in models of Alzheimer's disease and cancers.

By merging of hydrogel technology with polyphenol chemistry by building new polyphenol complex like polyphenol-protein and polyphenol-starch, researchers aim to make electrodes and sensors of NPs of polyphenol that are not only highly functional but similarly biocompatible, comfortable, stability and long-lasting. This could lead to medical devices as nanorods that blend seamlessly with the human body and protecting as biomedical devices, improving everything from patient comfort to the reliability of life-saving treatments.

Which help them defend counter to stress and give them colour and flever. For us, polyphenols are important because they can act like antioxidants, protecting our cells from damage caused by unstable molecules (free radicals). Interestingly, the same compounds can sometimes behave like pro-oxidants agent, meaning they increase stress inside harmful or abnormal cells and attack on harmful cell and tissues, which may help slow diseases like cancer.

Many common sources of polyphenols include grape seeds and skins, wild herbs like thyme, tea, fruits, and vegetables. Instead of letting agricultural by products like grape pomace go to waste and prevention of food, scientists are finding ways to reuse them as valuable resources rich in polyphenols and they are increase availability of polyphenol. This not only benefits human health but also supports a sustainable, ecofriendly approach by reducing food waste.

On the biological side, polyphenols interact with key systems in our cells, such as glutathione, which helps maintain balance between healthy and harmful oxidation it's a barrier between in healthy and harmful cells. This delicate balance explains why polyphenols can be protective in normal cells but destructive in diseased ones.

Altogether, polyphenols are gaining attention not just as food nutrients but as potential tools for illness deterrence, therapy, and sustainable product growth and food stoppage.

➤ *Structure of Polyphenol*

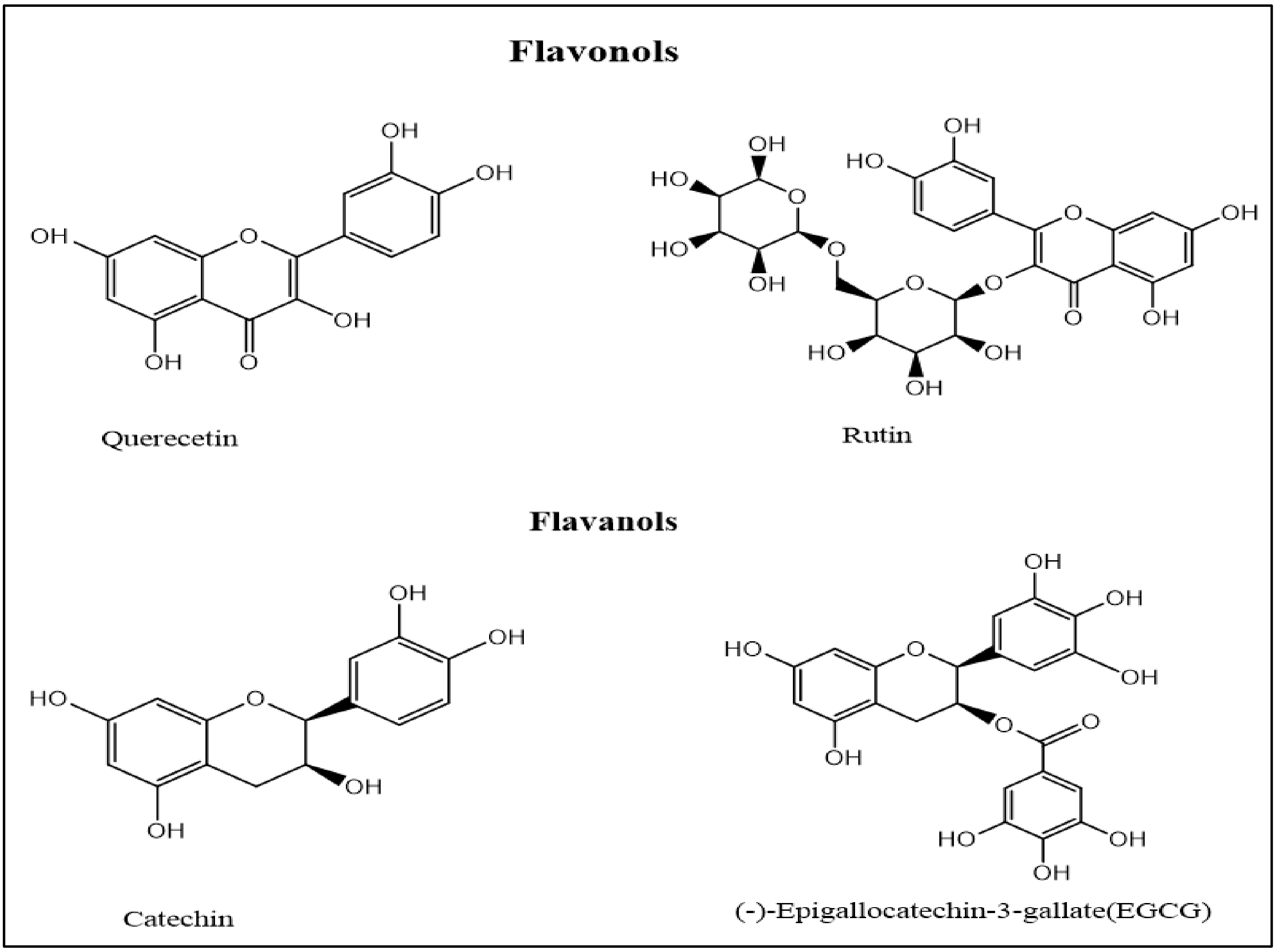

Fig 1 Flavonols

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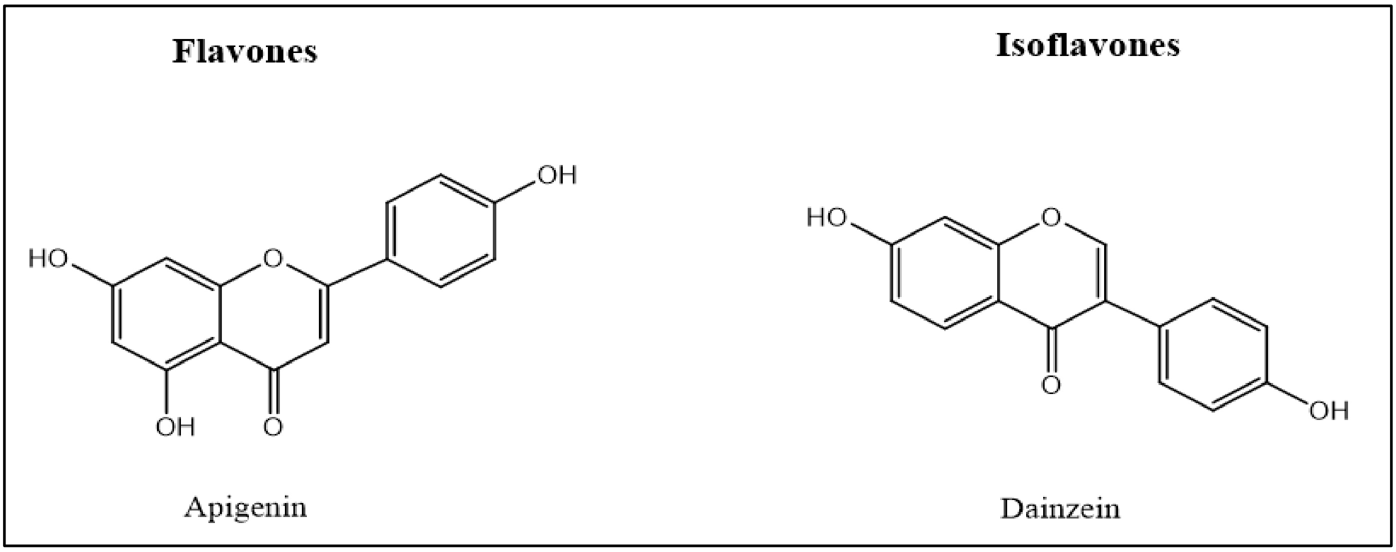

Fig 2 Flavones & Isoflavones

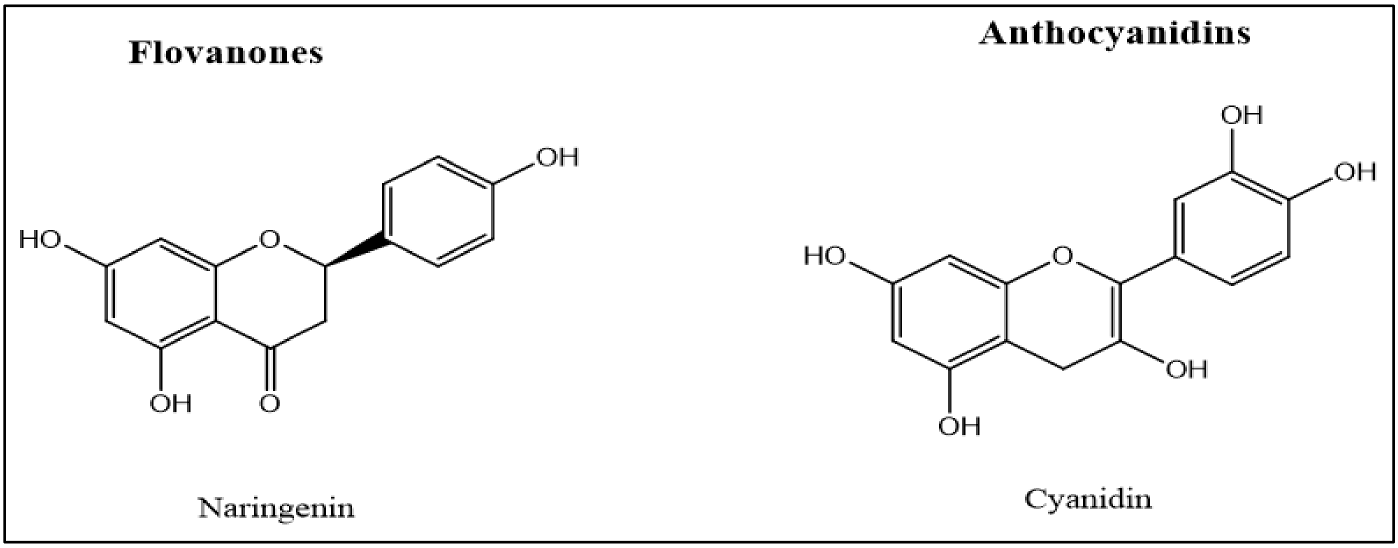

Fig 3 Flovanones & Anthocyanidins

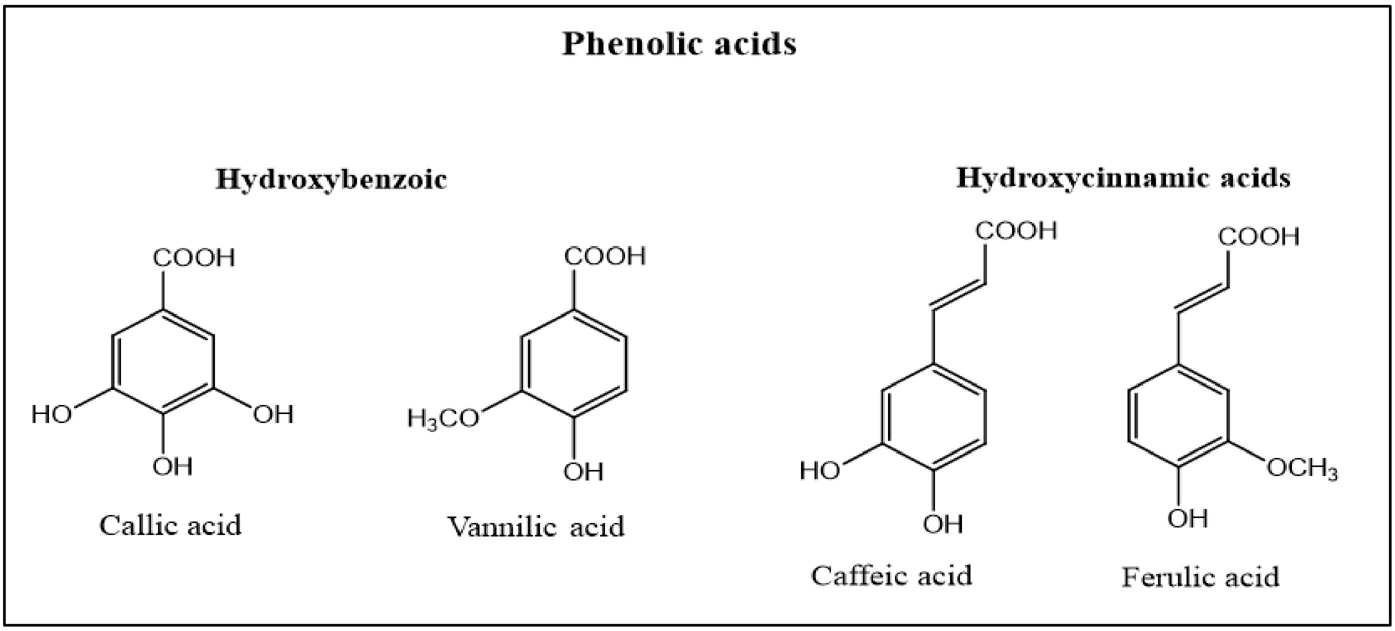

Fig 4 Phenolic Acids

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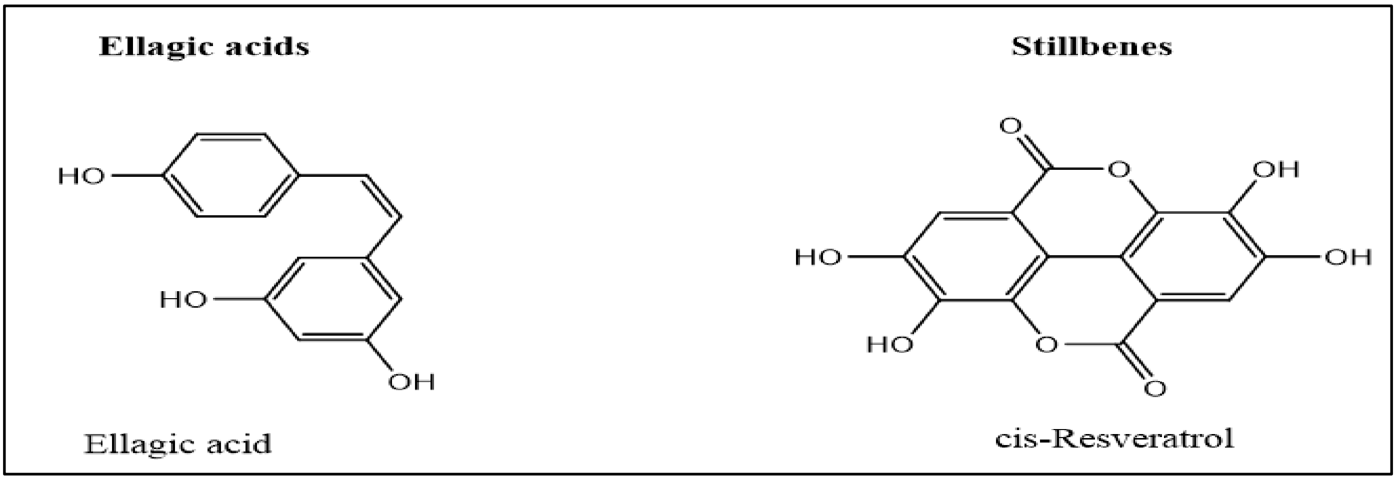

Fig 5 Ellagic acids & Stillbenes

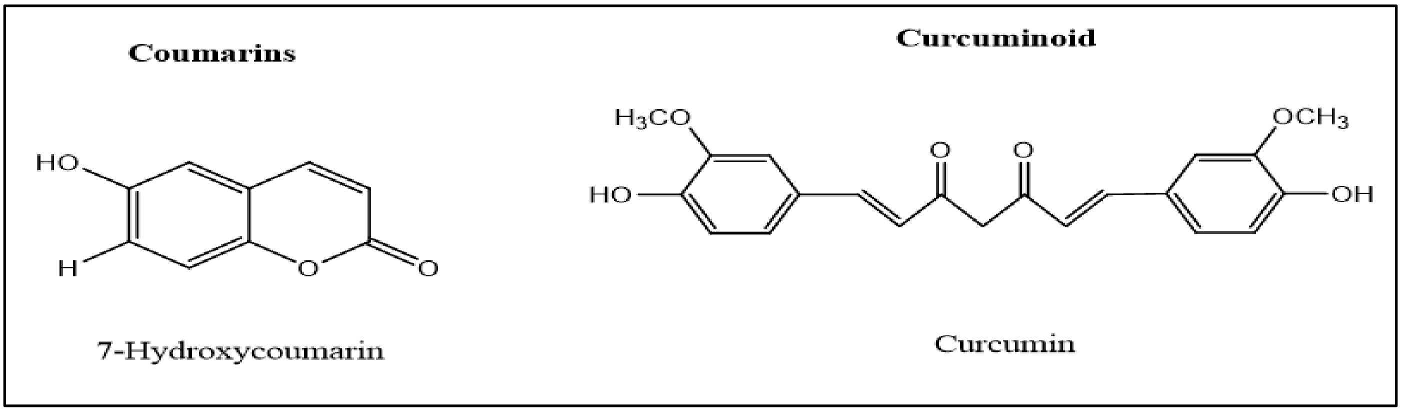

Fig 6 Coumarin & Curcuminoid

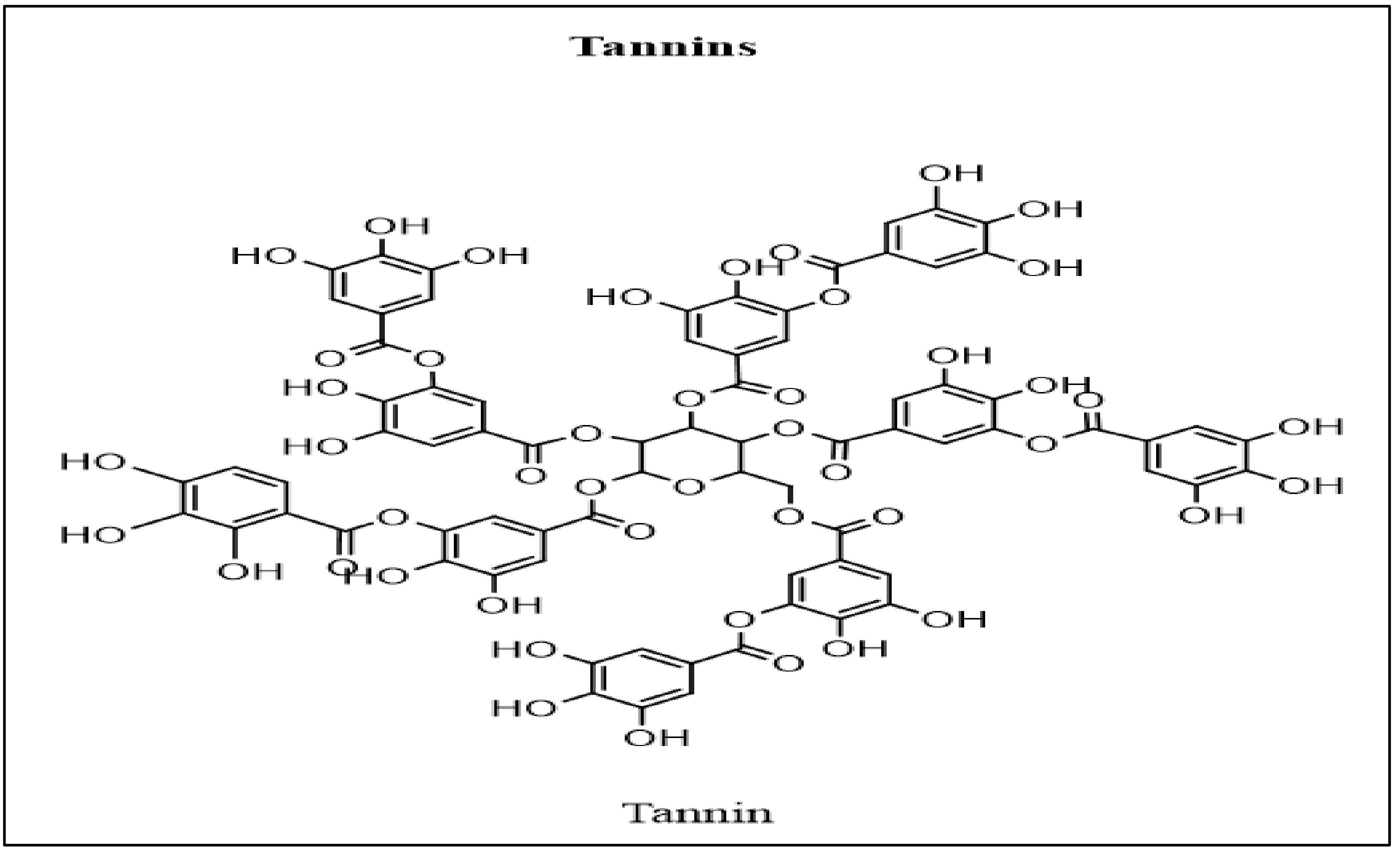

Fig 7 Tannins

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II. POLYPHENOL-PROTEIN COMPLEX

Polyphenols are natural compounds found in many plants. They can easily attach to proteins, and they are forming a complex which are called polyphenol–protein complexes. In nature, these complexes affect how plant materials break down in the soil and how nutrients like nitrogen are released, which in turn influences soil health and fertility[7].

At the same time, these complexes are very important in food and health research studies. Polyphenols-protein complex is known for their strong antioxidant powers, and on their own they can be stable and difficult break down. When they join with proteins, they become more stable and their health benefits are better preserved. This combination not only strengthens the antioxidant activity but also improves the functional properties of proteins, making them more useful in foods such as drinks, packaging films, and delivery systems for pharmaceuticals[8].

In more words say, polyphenol–protein complexes are valuable both in keeping soils fertile in nature and in creating healthier, more stable foods for people.

Fats and oils in food can easily spoil because of oxidation, which reduces their nutrition and can even form harmful compounds. To stop this, antioxidants are used. Synthetic antioxidants work well but may cause side effects. Natural antioxidants, such as polyphenols from plants, are safer and have strong health benefits[9].

Soy protein is a widely used plant protein with good nutrition, but it often needs modification to perform better in food systems. When polyphenols like EGCG attach to soy protein, they can improve its stability and antioxidant power. Adding natural polysaccharides such as pectin or CMC can further strengthen these complexes, making them more stable and useful in preventing oxidation[10].

This study looks at how combining soy protein, polyphenols, and polysaccharides can create safer, natural, and more effective antioxidants for food applications.

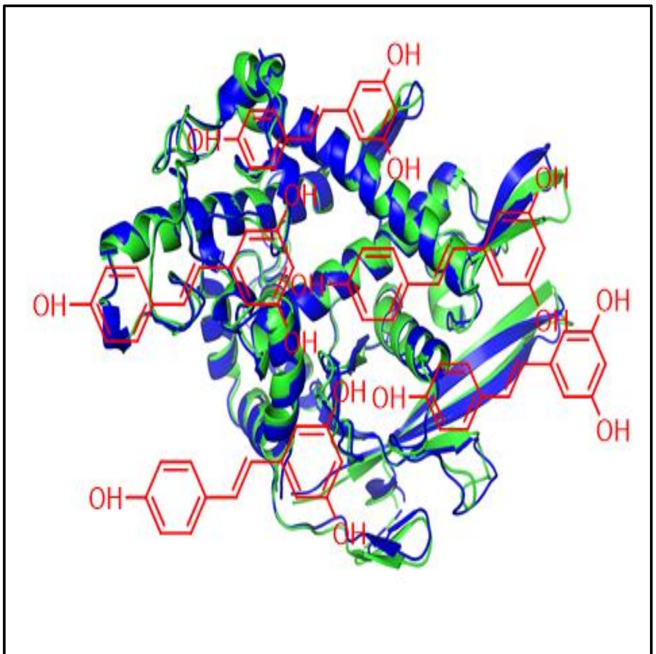
Beans like soy, peanut, and chickpea are not only good sources of protein but also contain polyphenols, there for high probability of present of polyphenol-protein complex. Natural plant compounds that help protect the body from damage in case of polyphenol-protein complex increases the stability of compound. These polyphenols can work as antioxidants, support heart health, and may even reduce the risk of diabetes and cancer. However, the way polyphenols exist in food affects how well our bodies can absorb them. Some polyphenols are easily absorbed, while others are locked inside the food's structure and need help to be released. Lactic acid bacteria, commonly used in fermentation, can break down complex food structures and release more polyphenols. This process not only improves the nutritional value of bean milk but also boosts its antioxidant power. Studying how fermentation changes polyphenols during digestion can help in developing healthier and more effective fermented bean milk products[11].

III. POLYPHENOL-PROTEIN INTERACTION

Researchers analyzed extensive data from the PDB and used molecular dynamics simulations to examine these interactions at an atomic level. They confirmed that polyphenols attach to various protein targets through noncovalent forces like hydrogen bonds, π−π stacking, and hydrophobic contacts[12]

A major finding is that water molecules are not just a passive background; they actively bridge and stabilize the bonds between polyphenols and proteins. This water-mediated interaction creates a dynamic and flexible binding mechanism, which explains why polyphenols can interact with a wide variety of proteins a trait known as binding promiscuity. Furthermore, the study showed that adding sugar groups (glycosylation), as with isoquercetin, changes a polyphenol's activity by often introducing new water-mediated bonds, which can alter its binding strength and selectivity[13].

The research underscores that polyphenol-protein interactions are complex, dynamic, and critically dependent on water. These insights are vital for understanding how these natural compounds promote health and provide a strong foundation for rational drug design, offering a path to developing safer, more effective treatments[14].



Protein-Stilbenes (resveratrol)

Fig 8 Protein-Stilbenes (Resveratrol)

➢ *Polyphenols Compounds Combined with Protein*

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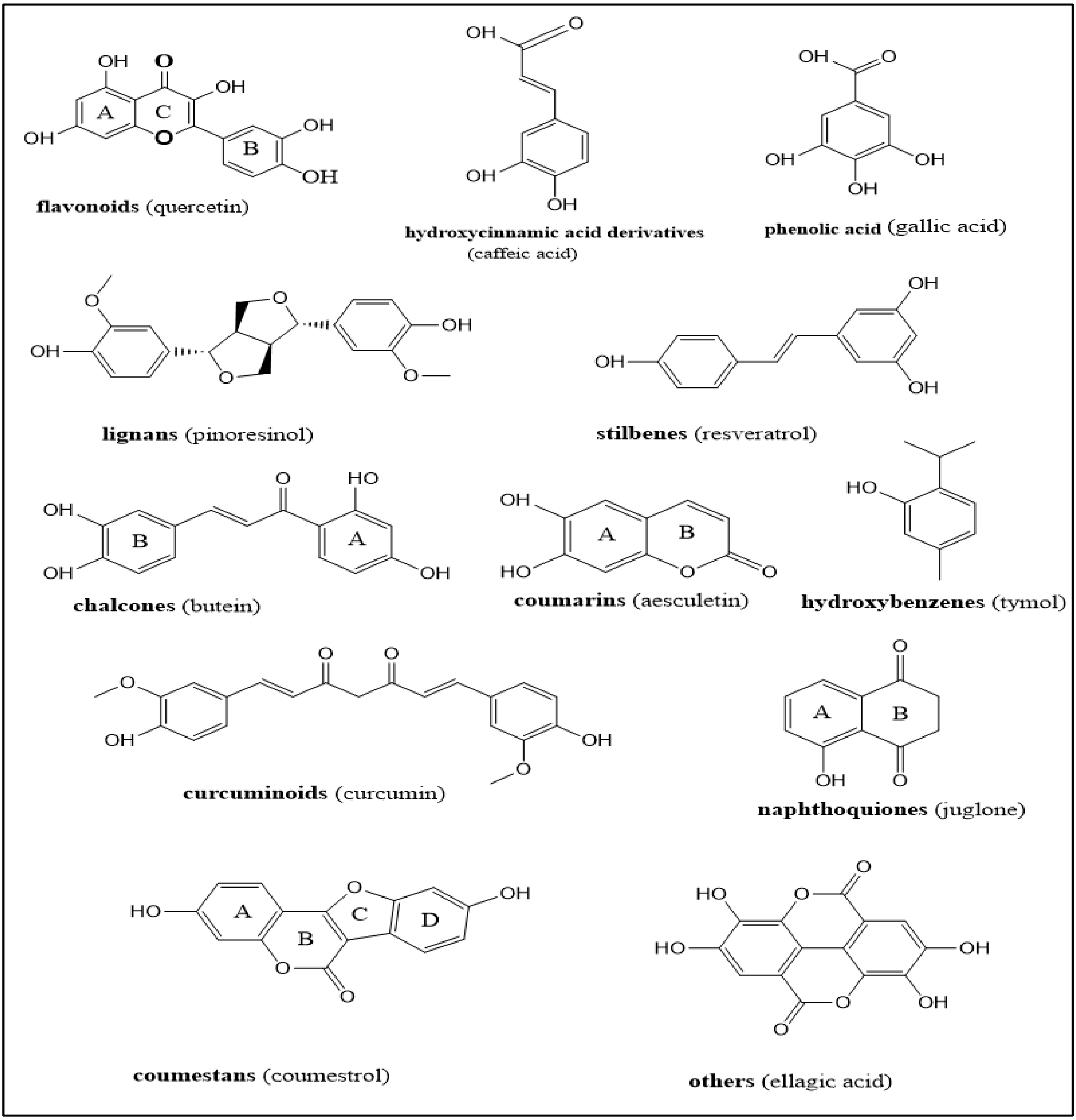

Fig 9 Polyphenols Compounds Combined with Protein

➢ *Polyphenol-starch complex*

Starch is a major dietary carbohydrate made of amylose and amylopectin, commonly found in many foods. It can interact with small molecules to form complexes that change its properties. Polyphenols are plant-derived compounds with strong antioxidant and health-promoting effects[15]. When starch and polyphenols combine, they create a starch-polyphenol inclusion complex. This structure protects polyphenols from degradation, enhances their stability, and allows controlled release in the digestive system, improving their bioavailability. At the same time, it slows down starch digestion, reduces blood sugar spikes, and acts like resistant starch, with potential prebiotic benefits for promoting healthy gut bacteria[16].

➢ *Combination of Polyphenol with Starch*

Starch is a natural carbohydrate that serves as a major energy source in foods. However, its digestion rate and structural stability can be influenced by interactions with other food compounds[17]. Among these, polyphenols naturally occurring antioxidants found in plants have shown a strong ability to interact with starch molecules through hydrogen bonding, hydrophobic forces, and electrostatic interactions. These interactions lead to the formation of

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starch-polyphenol inclusion complexes, especially the V-type crystalline structure, where the polyphenol molecules are trapped inside the helical cavity of amylose[18].

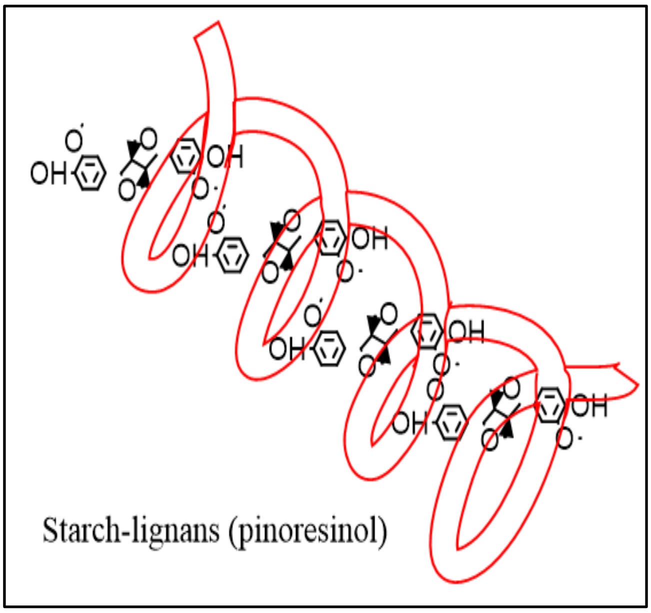

Fig 10 Starch-Lignans (Pinoresinol)

The combination of polyphenol and starch not only modifies starch's gelatinization, retrogradation, and digestibility but also enhances its nutritional and functional properties. Polyphenols can inhibit digestive enzymes like α-amylase and amyloglucosidase, slowing down starch breakdown and forming resistant starch (RS) a form beneficial for blood sugar control and gut health. The resulting complex is known as Type-5 resistant starch.

The efficiency of complex formation depends on factors such as the structure and hydrophobicity of the polyphenol, as well as the molecular motion behaviour of starch during processing (like heating, homogenization, or moisture treatment).

IV. MATERIALS AND METHOD

The materials utilized in these studies focused on food science and functional properties, primarily consisting of biomacromolecules like debranched rice starch, Riceberry rice flour, and myofibrillar protein gels isolated from chicken breast meat[19]. A wide array of polyphenols was used, including commercial standards like genistein, quercetin, naringin, and various stilbenes (resveratrol, pterostilbene, polydatin), as well as complex plant-based additives like blackcurrant juice and pomace, and extracts from Melissa officinalis and Centella *asiatica*. The main methods cantered on modulating the food matrix and analysing the resulting structural and functional changes. Modification techniques included six "green" physical methods (e.g., annealing, ultrasound, wet-microwave) applied to rice flour, and processes such as High-Pressure Homogenization and Heat Moisture Treatment to induce starch-polyphenol V-type inclusion complexes[20]. Characterization involved analysing the complexes ordered structures using methods like Differential Scanning Calorimetry (DSC) and X-ray Diffraction (XRD), and evaluating functional performance by measuring resistant starch (RS) content, inhibition of digestive enzymes (-amylase/amyloglucosidase), and in vitro antioxidant capacity (ABTS, DPPH, FRAP assays). The overall assessment was rounded out by measuring physicochemical properties (pH, colour, texture) and conducting sensory evaluations using trained panelists[21].

A. *Extraction from Plant*

Polyphenol is a wild group of plant secondary metabolites which extract by pure green synthesis. Extraction of plant pigments or polyphenols is an important process for obtaining natural antioxidants from fruits, vegetables, and medicinal plants. Conventional techniques such as maceration, Soxhlet, and heat-assisted extraction are simple and widely used but often require long extraction times, large amounts of solvents, and high energy consumption. To overcome these drawbacks, modern "green" extraction methods like ultrasound-assisted, microwave-assisted, enzyme-assisted, pressurized liquid, and supercritical CO_2 extraction have been developed. These techniques are faster, more efficient, and environmentally friendly, requiring less solvent while yielding higher-quality extracts. They preserve heat-sensitive compounds and enhance bioactive recovery. Due to these advantages, green extraction methods are increasingly used in the food, cosmetic, and pharmaceutical industries for producing natural, safe, and sustainable plant pigments and polyphenol-rich products.

➢ *Pressurized Liquid Extraction (PLE)*

Pressurized Liquid Extraction (PLE) is an advanced, eco-friendly technique increasingly used for extracting valuable bioactive compounds such as polyphenols, flavonoids, and antioxidants from plant materials. The process involves the use of elevated pressures (typically 100–120 bar) and moderate temperatures (40–80 °C) to maintain solvents like water and ethanol in a liquid state above their normal boiling points. This enhances the solvent's ability to penetrate plant cells, improving the solubilization and diffusion of target compounds. Compared to traditional extraction methods such as Soxhlet or maceration, PLE offers higher efficiency, shorter extraction time, and significantly lower solvent consumption.

According to the 2025 study on Teff grain, optimal PLE conditions (60 °C and 69.86 % ethanol) produced a high phenolic yield, extracting key compounds such as ferulic acid and p-coumaric acid, which showed strong antioxidant activity. The total phenolic content obtained by PLE was nearly double that of conventional methods, while also preserving thermolabile compounds by reducing oxidation and degradation. Furthermore, PLE-generated extracts displayed superior antioxidant activity in assays like ORAC, ABTS, and DPPH, indicating the method's efficiency in recovering functional bioactives.

Compared with Expanded Solvent Extraction (ESE), PLE is easier to operate, more adaptable for industrial scale-up, and compatible with common green solvents such as water and ethanol. While ESE may offer higher selectivity

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and lower environmental impact due to CO_2 recyclability, PLE stands out for its versatility, reproducibility, and lower equipment complexity. Thus, PLE represents a sustainable and effective extraction method, ideal for producing high-quality natural extracts used in food, cosmetic, nutraceutical, and pharmaceutical industries, aligning well with modern green chemistry and clean-label production standards.

- *Mechanism of Pressurized Liquid Extraction (PLE)*

✓ *Step 1: Heating the Solvent*

The solvent (water, ethanol, or their mixture) is heated to a moderate temperature, which reduces its thickness and increases its ability to dissolve plant compounds.

✓ *Step 2: Applying High Pressure*

High pressure is used to keep the solvent in liquid form even at high temperatures. This makes the solvent more stable and more effective at extraction.

✓ *Step 3: Forcing Solvent into Plant Material*

The pressure pushes the hot solvent deep into the plant cells, helping it enter tiny pores and loosen cell structures.

✓ *Step 4: Releasing Plant Compounds*

The heat and pressure work together to break cell walls, allowing compounds like polyphenols and pigments to dissolve into the solvent.

✓ *Step 5: Transporting Extracted Compounds*

The dissolved compounds move out of the plant material and are carried away by the flowing solvent.

✓ *Step 6: Collecting the Extract*

The solvent and extracted compounds exit the chamber. The extract is collected, and the solvent can be evaporated or reused.

➢ *Supercritical Fluid Extraction (SFE)*

Supercritical Fluid Extraction (SFE) is a modern and eco-friendly method used to extract valuable natural compounds like oils, pigments, and antioxidants from plants[22]. It mainly uses carbon dioxide (CO_2) as a solvent, which becomes a "supercritical fluid" when heated and pressurized above certain levels (around 31°C and 74 bar). In this state, CO_2 behaves like both a liquid and a gas — it can easily move through plant materials and dissolve useful compounds very efficiently. SFE is considered a green technology because CO_2 is safe, non-toxic, and leaves no harmful residues in the final extract. It also protects sensitive compounds from heat damage and produces very pure extracts in a short time. Sometimes, a small amount of ethanol is added to help extract more polar compounds such as polyphenols. Compared to older methods, SFE gives higher-quality and cleaner extracts while using less energy and chemicals. Although it needs expensive equipment and careful pressure control, it is widely used in making herbal medicines, cosmetics, essential oils, and caffeine-free coffee. Overall, SFE is an advanced, sustainable way to get natural ingredients without harming the environment[23]

- *Mechanism of Supercritical Fluid Extraction (SFE)*

✓ *Step 1: Converting CO_2 to Supercritical State-*

CO_2 is heated and pressurized until it becomes supercritical, gaining strong dissolving power.

✓ *Step 2: Penetrating the Plant Material-*

Supercritical CO_2 enters tiny pores of the plant because of its gas-like ability to move easily through materials.

✓ *Step 3: Dissolving Target Compounds-*

Once inside, the supercritical CO_2 dissolves oils, pigments, polyphenols, and other desired compounds due to its liquid-like behavior.

✓ *Step 4: Carrying Compounds Out-*

The dissolved compounds are carried by the flowing supercritical CO_2 out of the extraction vessel.

✓ *Step 5: Pressure Reduction-*

The pressure is lowered, causing CO_2 to return to gas form. When this happens, the extracted compounds separate easily.

✓ *Step 6: Collecting the Extract-*

The pure extract is collected, and CO_2 can be recycled and reused, making the process clean and environmentally friendly[23]

➢ *Heat-Assisted Extraction*

Heat-assisted extraction is a widely used technique because applying heat makes the whole extraction process faster and more efficient. When plant material is heated in a solvent like water, ethanol, or their mixture, the cell walls loosen, allowing the solvent to enter more deeply. This improves the release of polyphenols and other useful compounds. Heating also reduces the viscosity of the solvent, so it flows more easily through the plant tissues, increasing mass transfer. As temperature rises, the solvent's surface tension decreases, helping it wet the plant particles better and improving contact between solvent and plant material[24].

Using a mixture of ethanol and water is often preferred in HAE because heat changes the polarity of solvents. Hot ethanol–water mixtures can dissolve both polar and moderately non-polar compounds, making extraction more effective than using a single solvent. The technique also provides good yields within a relatively short time compared to traditional maceration[25].

However, temperature must be carefully controlled. Although heat improves extraction, very high temperatures or extended heating can degrade sensitive polyphenols, causing oxidation, polymerization, or loss of antioxidant activity. Some studies show that after a certain point, increasing time does not improve yield and may even reduce the quality of the extract. Therefore, the balance between temperature, solvent type, and extraction time is essential[26].

Overall, heat-assisted extraction is simple, economical, and suitable for many aromatic plants, especially those from

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the Lamiaceae family. It is commonly used in both research and industry to obtain high-quality extracts with increased polyphenol content[27].

- *Mechanism of Heat-Assisted Extraction (HAE)*

Heat-Assisted Extraction works by using elevated temperature to improve the release of bioactive compounds from plant materials[28]. When heat is applied, several physical and chemical changes occur inside the plant matrix and solvent:

✓ *Softening and Breakdown of Plant Cell Walls*

Heat weakens the structure of cell walls, causing them to loosen or partially break. This increases permeability, allowing the solvent to enter the tissues more easily and reach the polyphenols and other compounds trapped inside[29].

✓ *Increased Solubility of Compounds*

As temperature rises, the solubility of polyphenols and many phytochemicals increase. This allows more compounds to dissolve in the solvent, improving the extraction yield. Your PDFs highlight that higher temperatures enhance the recovery of polyphenols by increasing solubility[30].

✓ *Reduced Viscosity and Surface Tension of the Solvent*

Heat lowers viscosity and surface tension, making the solvent thinner and allowing it to move more freely through plant tissues. This improves mass transfer and speeds up extraction[31].

✓ *Faster Diffusion Rate*

Warm conditions boost molecular movement, so compounds diffuse out of plant cells more quickly into the solvent[32].

✓ *Enhanced Mass Transfer*

Heat accelerates the movement of compounds from plant tissues to the solvent by increasing kinetic energy and reducing physical barriers[33].

➢ *Ultrasound-Assisted Extraction*

UV extraction is a modern green technique used to release valuable plant compounds such as polyphenols, flavonoids, and antioxidants. Like other advanced extraction methods described in your PDFs, UV extraction aims to improve efficiency, reduce solvent use, and protect heat-sensitive compounds. In this method, plant material is exposed to ultraviolet (UV) light before or during the extraction process. The UV light provides energy that weakens or breaks the outer plant cell walls. This disruption makes it easier for solvents such as water, ethanol, or methanol to enter the tissues and dissolve the desired compounds[34].

UV light also helps increase mass transfer, similar to how heat, ultrasound, or microwave energy enhances extraction in the other PDFs. By creating micro-cracks in the cells, UV exposure reduces resistance to diffusion, so polyphenols move more freely from the plant matrix into the solvent. The process works at low temperatures, which helps preserve sensitive compounds that might degrade under high heat[35]

Another benefit is that UV pretreatment reduces extraction time because the plant structure becomes softer and more permeable. UV light can also reduce microbial load on plant surfaces, contributing to cleaner extracts. The method is considered environmentally friendly because it requires less energy and fewer chemicals compared to traditional extraction methods like reflux or Soxhlet.

Overall, UV extraction combines the advantages of green technology, low temperature processing, and improved cell-wall disruption. It provides a fast, gentle, and efficient way to recover high-quality bioactive compounds from plant materials.

- *Mechanism of UV Extraction Method*

✓ *Step 1: UV Light Exposure*

Plant material is exposed to ultraviolet (UV) light. UV rays provide high-energy radiation that interacts with surface cells.

✓ *Step 2: Photochemical Reactions Begin*

UV energy breaks chemical bonds in the plant cell wall, lignin, cellulose, and pectin structures start weakening[36].

✓ *Step 3: Formation of Micro-Cracks / Pores*

Small cracks, pores, and openings appear on the cell surface. the plant tissue becomes more porous and easier for solvent penetration.

✓ *Step 4: Increased Solvent Penetration*

Solvent (water, ethanol, etc.) enters more easily through the UV-created pores. contact between solvent and target compounds (polyphenols, flavonoids, pigments) increases.

✓ *Step 5: Faster Diffusion of Compounds*

UV light energizes molecules inside plant cells. this increases diffusion, allowing compounds to move quickly from inside the cells into the solvent[37]

✓ *Step 6: Enhanced Release of Bioactive Compounds*

Polyphenols, antioxidants, and other molecules dissolve more efficiently. extraction speed and overall yield improve.

✓ *Step 7: Protection of Heat-Sensitive Compounds*

Because UV extraction works at low temperature, heat-sensitive compounds do not degrade. final extract retains better antioxidant and nutritional quality.

✓ *Step 8: Reduction in Microbial Load (Optional Benefit)*

UV light can damage microbes on the plant surface. This leads to cleaner, safer extracts[38]

V. CONCLUSIONS

➢ *Polyphenols as Dual-Action Bioactive Compounds –*

Polyphenols are naturally occurring metabolites obtained from plant and has characteristics pro-oxidant and

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dual antioxidant behaviour. Due to its antioxidant behaviour it used to protect healthy cells by reducing oxidative stress, neutralizing free radicals that prevent cell from disease like cardiovascular disorders, and neurodegenration. Due to its controlled pro-oxidant action that selectively target abnormal or cancerous cell by making it promising in therapeutic applications. Furthermore, polyphenols can interact with cellular redox system that help in maintaining homeostasis in normal cells including glutathione metabolism that used in suppressing harmful cell pathway in diseased tissue. These unique properties provide polyphenols as key natural agent in health research and modern food science.

➢ *Functional Polyphenols-Protein and Polyphenol-Starch Complexes-*

Complex formation of polyphenols and biomolecules such starch and protein that has various benefits. Polyphenols-protein enhance stability of protein, antioxidant properties, used in preservation of food, pharmaceutical delivery systems, and biodegradable packaging. Similarly, it increases resistant of starch content, improved metabolic, slow down starch and digestive health outcomes. These complexes improve bioavailability and allow controlled release in human body and prevent from degradation. They contribute to develop functional food and nutraceuticals that promote better health by adding new techniques for the enhancement of food processing.

➢ *Advancement in Green Extraction Technologies*

Such as Supercritical Fluid Extraction (SFE), Pressurized Liquid Extraction (PLE) and Ultrasound-assisted methods has developed polyphenol recovery. These eco-friendly techniques confirm better purity, high yield, and decrease environmental effect while transforming agricultural wastes into valuable resources. The integration of nanotechnology, hydrogels, and biosensor development further strengthens the role of polyphenols in future industrial applications and biomedical. Overall, polyphenols complexes offer sustainable resolutions to food safety, global health and environmental challenges, positioning them as crucial ingredients in next-generation useful products and environmental sustainability.

FUTURE ASPECTS

➢ *Targeted Drug Delivery*

Development of polyphenol-based nanoparticles for controlled drug release.,Improved cancer-cell targeting through pro-oxidant activity.

➢ *Polyphenol–Protein Complex Technology*

Increasing protein stability and antioxidant performance in foods, Enhancing pharmaceutical delivery systems with better biological interaction.

➢ *Polyphenol–Starch Functional Foods*

Slowing starch digestion to prevent sharp blood-sugar spikes, Supporting gut health by, promoting resistant starch formation, Neuroprotective Applications, Reducing oxidative stress and inflammation in brain cells, Preventing or delaying neurodegenerative disorders like Alzheimer's.

➢ *Expansion of Green Extraction Techniques*

Wider industrial use of eco-friendly PLE, SFE, and NADES methods, Lower cost and higher yield of heat-sensitive polyphenols.

➢ *Sustainable Waste Recycling*

Extracting polyphenols from grape pomace, tea waste, fruit skins, etc, Reducing environmental pollution and supporting circular economy.

➢ *Bioactive Packaging Materials*

Extending shelf life by inhibiting oxidation and microbial growth, Reducing dependency on synthetic preservatives and plastics.

➢ *Immune Boosting & Anti-Aging Therapies*

Modulating cellular redox balance to support immune function, enhancing collagen protection and reducing oxidative skin damage.

➢ *Personalized Nutrition and Functional Beverages*

Designing foods based on individual gut microbiome response, Fortifying drinks and supplements with stabilized polyphenol complexes.

➢ *Biomedical Devices & Soft Electronics*

Polyphenol-infused hydrogels for wound healing and tissue adhesion, Conductive polyphenol nanostructures for biosensors and implants.

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