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Review Article

Exploring Plant Phenolic, Functional Roles, Extraction and Future Perspectives

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Abstract

Plants produce phenolic compounds as part of their secondary metabolism. They are essential for plant growth, development and protection. Phenolic compounds have many types such as flavonoids, tannins, lignans, stilbenes and many more. They occur in many structural forms and are produced through specific biosynthetic pathways. These pathways by which phenolic acids are produced are shikimic acid pathway and aceto-malonate pathway. These pathways supply the necessary precursors for a diverse range of phenolic compounds in plants and microorganisms. Plant phenolic compounds exhibit a dual role attracting symbiotic microbes and pollinators while simultaneously repelling pests and herbivores. Plants use phenolic compounds to protect them against abiotic stress by collecting them in response to factors like drought, oxidative stress, salinity and extreme temperatures. Because of their high antioxidant characteristics, these compounds are most abundantly used in pharmaceutical, cosmetics, and textile and food industries.

Keywords: Aceto-malonate pathway; Abiotic stress; Flavonoids; Phenols; tannins; Symbiotic microbes:

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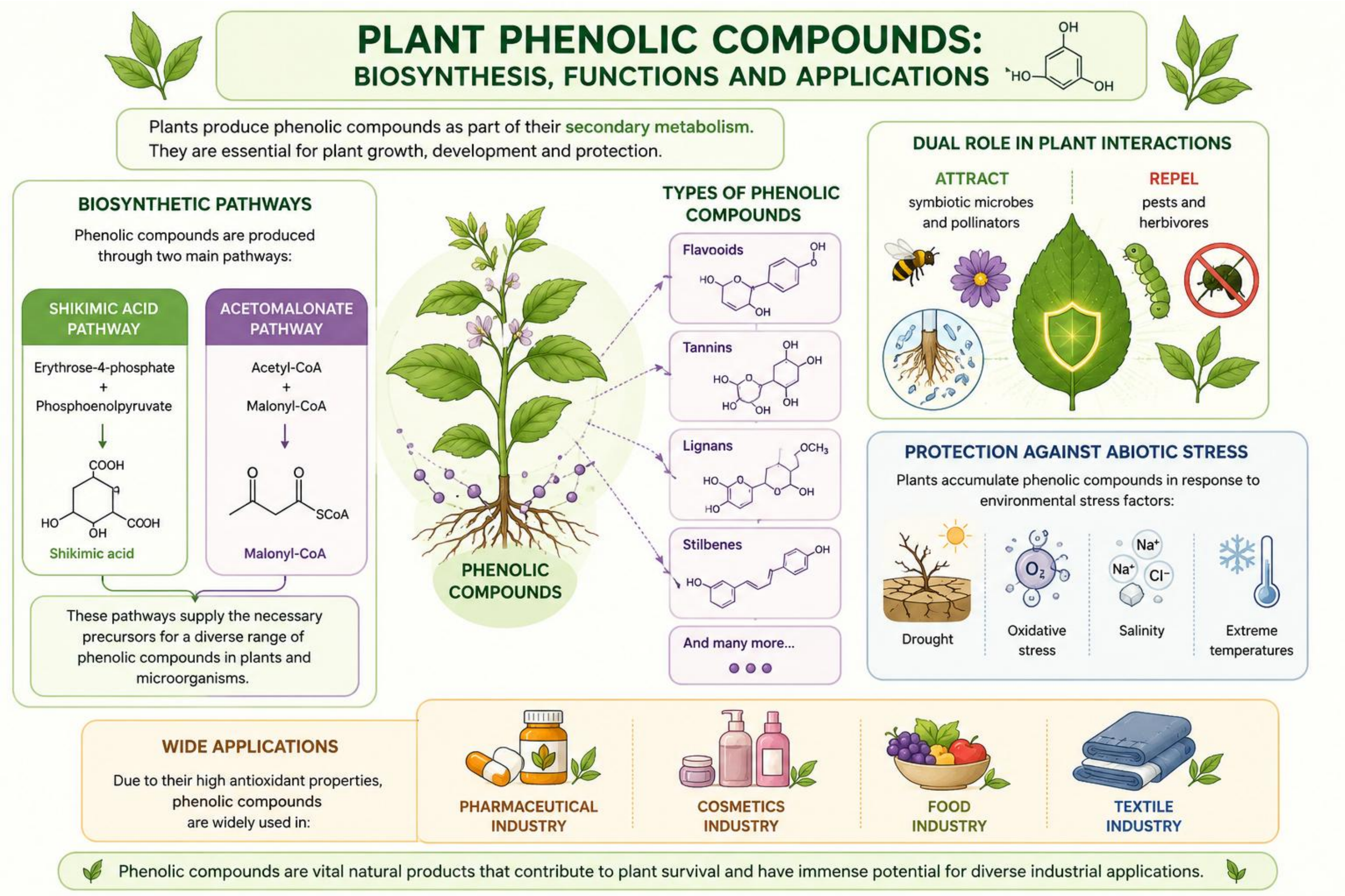
Graphical Abstract:



1: Introduction

Plants are producing an incredible diversity of natural products and the most important are phenolic compounds. They are the stout outcome in kingdom plantae. Humans have been aware of their existence from centuries, because they were product of interest and play important role in plant nutrition, growth, fertility and protection. These are the most common allelochemicals in the ecosystem used as anti-herbivore chemicals (Pratyusha, 2022). These compounds are universally found in Kingdom Plantae. Phenolic are unusually found in algae, fungi and also in bacteria. Plant phenolic are a diverse group of natural organic molecules characterized by an aromatic ring with one or more hydroxyl groups attached to the ring. Phenolic compounds exhibit a wide structural diversity spanning from simple, low molecular weight molecules with a single aromatic ring, to large, intricate tannins and other derived polyphenols (Kumar *et al*., 2023). Phenolic compounds are located in vacuole in the cell. However, in young plant tissues, whose cells have vacuoles which are weakly developed, phenolic compounds are found in chloroplasts and nucleus. The formation of phenolic substances is the fundamental part of plant metabolites (Babenko *et al*., 2019). Plant phenolics are a chemically diverse and heterogeneous group. Phenolic compounds exhibit varied solubility; while some, such as carboxylic acid and glycosides are water soluble, the majority are only soluble in organic solvents. Other groups of phenolics form insoluble polymers. Phenolic compounds are generally found in many plant parts such as nuts, vegetables legumes, grains, spices and fruits, playing important roles in numerous physiological mechanisms such as plant quality, pigmentation, flavor, and adaptive responses to stress (Zhang, *et al*., 2022). Plant phenolic protect plant from viruses, predators and parasites as well as ultraviolet (UV) rays and are significant because they give colors to plants. Fruits (berries, apples, and strawberries), vegetables (Broccoli, onions, and spinach), herbs and spices are rich in phenols. It has been determined that about 2% of carbon fixed through photosynthesis in plants is used for the production of flavonoids or structurally related compounds. Higher plants create a wide variety of phenolic compounds and the known count of these compounds is always growing. Leaves of vascular plants contain diverse array of soluble compounds such as amides, esters and glycosides derived from hydroxycinnamic acids; they also contain glycosylated Flavonoids, particularly flavones; along with proanthocyanidins and their related compounds. Examples of phenolic-containing polymers in plants are suberin, pollen sporopollenin and lignin. Chlorogenic acid is a soluble phenolic and is commonly found across different species.

1.1: Classes of phenolic compounds

Phenolics are classified into different classes based on their fundamental carbon skeleton which includes simple phenols to complex phenols. Benzoquinone is a chemical structure contain 6 carbon aromatic ring. Phenolic acids contain 6 carbon aromatic ring and one carbon side chain (C6—C1). Acetophenone, and phenylacetic acid (C6—C2) contain one aromatic ring and 2 carbon side chain. Hydroxycinnamic acid, phenylpropanes, chromones and coumarins contain one aromatic ring and three carbon side chain. Naphthoquinones contain one aromatic ring and 4 carbon side chain. Xanthones contain 2 aromatic rings linked by single carbon atom. Stilbenes and anthraquinones consist of two aromatic rings linked by two carbon atoms. Flavonoids, isoflavonoids, neoflavonoids contain 2 aromatic rings linked by 3 carbon atoms. These are present universally throughout higher plants. Low-molecular-weight phenolics include compounds that are widespread across various species as well as those that are unique to a single species. Condensed tannins have high molecular weight and are also called proanthocyanidins. They are most common phenols and are characteristics of woody plants and largely absent from herbaceous ones. Polyphenols also present in woody plants.

1.2: The functions of Phenols in the Kingdom Plantae:

Polyphenols are distributed across entire kingdom plantae, with its occurance varying by phylum. Bryophytes are known to regularly produce phenolic including bioflavonoids; however, it is within tracheophytes that the complete spectrum of phenolics has been identified. This phenolic compounds have persisted through natural selection and have evolved over time in terms of types and functions. Taxonomists frequently utilize these compounds to distribute and differentiate plantae specie. Unlike animals, plant manufacture this Polyphenols as a means of chemical defense against predators, given their stationary nature which prevents them from fleeing. The initial accepted function of Polyphenols are ecologic with few exhibiting two or even numerous functions. Numerous research have demonstrated the significant amount of compartmentalization of polyphenols and enzyme participate in the biogensis which exist through various route (Pratyusha, 2022).

Polyphenol fulfill a dual role by both force and captivate various living thing in the vicinity of the plantae These function as protector restrain, natural poisonous to animals, and pest resisting living thing such a vegetarian roundworm phytophagous insects, and fungous and bacteria infectious agen. Simple carbolic acids, complicated tannic acid and phenolic formaldehyde resins present on the plant emerge deter fowl by interacting along their intestinal flora and impairing their gastrointestional tract capabilities. Additionally, the scent and colorotion provided by down molecular-weight 1-phenyl-1-propanol first-hand captivate coordinated microbes, cross pollinate and creature that help in the scattered of fruits (Bhattacharya *et al*., 2010).

A diverse range of both easy and complicated polyphenols accumulate in herbage serviette serving as phytoalexins, phytoanticipins, and roundworm opposition geophilous infectious agents and herbivore bug. As a result, Polyphenol existed presented for a long time as effective alternatives to chemical methods for managing agricultural crop pathogens. polyphenol are produced when plant patterning identification receptors identify theoretical infectious agent through saved pathogen-associated mole within cular patterns (PAMPs), which activates pathogen-associated mole within cular patterns triggered immunity.This mechanism effectively restricts the spread of infection long Before the pathogen can completely establish itself the plantae.(Bhattacharya *et al*., 2010)

1.3: The function of phenols in growth of plants:

The majority of Polyphenols perform significant function in promoting plant growth aiding in the formation of cell walls. Phenylpropanoate, particularly 4-hydroxycinnamic acid and Fumalic acid have been located within nonsoluble or cell wall as ester. The reservoirs of wall-bound polyphenol act as a source of phenylpropanoid units necessary for lignin biogenesis, or they may signify the early stages of lignified. These esters, which encompass a considerable number of bound particles, are essential for the transmission of light energy, directing to alter in the structure of plant cell walls, water movement, hydrostatic pressure, and overall development. Auxin, and 3-indoleacetic acid an important growth regulating hormone, is crucial in the regulation of plant development (Pratyusha, 2022).

Plants are generally fixed in their locations and are unable to move, however, they do display various forms of movement. The leaf movement characterized by circadian rhythm refferd as nyctinastic has been documented in all leguminous species. The movement of leaves exhibiting nyctinastic is triggered by expanding and contractions of motor cell located in pulvini, which are situated at joints of the leaves and are considered to be regulated by Schildknecht turgorins, which are responsible for the leaf-closing actions in these plants. These turgorins constitute a new class of plant hormones that influence the hydrostatic pressure in plants. Among the recognized polyphenols turgorins include gallic acid 4-O-(β-D-glucopyranosyl-6′-sulfate) and gentisic acid 5-O-β-D-glucopyranoside, both present in the pulvini of Mimosa pudica L. Additionally, cis-p-coumaric acid 4-o-β-D-glucopyranoside is found in Cassia mimosoides L., while cis-p-coumaroylagmatine has been recognized in Albizia julibrissin Durazz. Consequently, polyphenols perform role in movement of plants. In seeds that sprout quickly, there is a higher concentration of coumaric acid β-glucoside, while seeds that do not germinate, like *Melilotus alba*, possess a notable amount of free coumarins. Furthermore, ferulic acid, which is another naturally occurring phenolic compound, acts as an inhibitor supress of seed development. These phenolic compounds serve as growing suppress by hindering the transfer of amino acids and the synthesis of protein within seed (Pratyusha, 2022).

1.4: The function of phenols in signaling of plant:

Allelochemicals are acknowledged for their interactions among dual plants. Polyphenols affect various natural and artificial nutriments in their surroundings. They impact the break down rate and perform a function in the nutrition cycle by either prohibit or facilitating spore formation. Polyphenols act as potent allelochemicals afford in whole parts of plant. Phenolic leaf allelochemical include propanoate, particularly 4-hydroxycinnamic acid, as well as how rhizosphere and root secretion that contain juglone, quercetin sorgoleone, and catechin compound. Polyphenols, found within the vacuoles of plants, engage with cytoplasmic proteins to create polyphenol-protein complexes. This complicate elevate the aging process of plants tissue and is responsible for the brown hue seen in aging leafage. Bioflavonoids, including rac-eriodictyol and apigenin-7-Oglucoside, extracted from pea root give off, have been identified as contributors to the triggered gene expression of nod. Additionally, natural bioflavonoids such as chalcones, hesperitin, naringenin, and isoflavonoids like genistein and daidzein, which are free by legume plants, stimulate nod genetic observation. Phenols, especially those found in significant flavonoids, participate to the coloring of fruits and flowers in plants, facilitating pollinator and the scattering of seeds. For example, kaempferol, apigenin, quercetin, luteolin and myricetin generate cream, lemon, and pasty hues in specific areas within plantae (Pratyusha, 2022).

2: Materials and Methods:

Study was performed a systematic literature search from 2000 to 2026 on PubMed, Scopus, Web of Science, Google Scholar and Science Direct. The keywords used were:Aceto-malonate pathway; Abiotic stress; Flavonoids; Phenols; tannins; Symbiotic microbes:

Only original papers, review articles and book chapters published in English were included. Animal waste studies, abstracted papers and papers with limited access were not included. Titles, abstracts and full texts were screened by two independent reviewers. Disagreements were resolved by discussion or consultation with a third reviewer. The data obtained were collected in a standardized form through the collections of waste type, bioactive compounds, extraction methods, bioactivity, and business models.

A narrative synthesis methodology was used because of the heterogeneity of studies. The quality assessment criteria were experimental design, protocol reproducibility and relevance. No human or animal subjects were used and so no ethical approval was needed.

3: Results and Discussion

3.1: Types and structure of phenolic compounds:

Phenolic compound are a class of organic molecules characterized by the presence of one or more hydroxyl group directly bonded to benzene ring, leading to a variety of distinct chemical structure. Phenolic compounds are divided into different groups: phenolic acids, flavonoids, tannins, stilbenes, and lignans (Albuquerque *et al*., 2021)

3.2: Phenolic acid:

Phenolic acid is divided into two groups. One is hydroxybenzoic acid and second is hydroxycinnamic acid. Hydroxybenzoic acid is obtained from benzoic acid and hydroxycinnamic acid is obtained from cinnamic acid. Some common phenolic acid are caffeic acid and ferulic acid which is present in berries, olives and coffee beans. (Albuquerque *et al*., 2021)

3.3: Flavonoids:

Flavonoids, are a significant class of secondary metabolites commonly present thought out the plant kingdom. Over 10,000 different flavonoids compound have been isolated and identified with widespread occurrence in fruits, vegetables, defensive herbs, nuts, cereals, flowers, stem and seed. (Chen *et al*., 2023) Flavonoids are a series of compounds with diphenylpropanes (C6–C3–C6) as the basic skeleton and two benzene rings bonded to each other through the central 3-carbon bridge. (Chen *et al.*, 2023). In higher plants, Flavonoids are responsible for the vibrant colors in flowers and fruits, which helps attract pollinators and seed dispersers.

Flavonoids help the plant form beneficial relationships with certain soil bacteria (symbiotic relationships). Flavonoids protect the plant from diseases caused by pathogens and from being eaten by insects. Flavonoids act as a natural filter to block harmful UV radiation from the sun. (Kumar *et al.*, 2020)

Flavonoid is known for its anti-inflammatory and anti-allergic effects, antioxidant, antithrombotic and vaso protective properties. Some flavonoids have antibacterial and antifungal properties. Flavonoids also function as a natural defense mechanism, protecting plants against microbial infections and insect infestations.

3.3.1: Properties of Flavonoids:

Flavonoids typically dissolve well in water and alcohol, though they are insoluble in organic solvents. Their genin components, however, dissolve only slightly in water but are soluble in ether. When flavonoids are mixed with alkalis, they create a characteristic yellow solution; adding acid to this solution will cause it to lose its color and become transparent again. Flavonoids have various subdivision, which include chalcones, flavones, flavonols and isoflavones. These subdivision have specific sources. For example, Apples, berries, and red cabbage are key dietary sources of the beneficial plant compounds known as flavonols and flavones. (Panche *et al*., 2016)

3.3.2: Flavones:

Their structure is just like flavonols, but hydroxyl group is not present on the C3 and the double bond is present between C2 and C3 (Albuquerque *et al*., 2021).The main flavonoids of this group are rutein, leutein, and luteolin glycosides. Apigenin and chrysin are prominently found as primary constituents in plant belongings to the Ochnaceae family (Fig 1). The major dietary sources of flavones are leafy green vegetables, spinach along with herb such as mint and chamomile. They are found in several plants such as Aloe vera, *Mentha longifolica* of Lamiaceae family, and *Momordica charantia* of Cucurbitaceae. (Roy *et al*., 2022)

3.3.3: Isoflavones:

Isoflavonoids are a specialized class of flavonoids (Fig 1). Some isoflavones have also been isolated from pea pods, seeds, and seed coats. Isoflavones have effective role in treating a number of disease. It has also been used to regulate hormone levels, as it binds to estrogen receptors and acts as a selective and agonist of estrogen receptors. It regulates the concentration and receptor of Endogenous estrogen and the identification of target tissues. And the biological effect of isoflavonoids on intestinal bacteria was studied, because bacterial enzymes in the intestine convert isoflavonoids into Different metabolites. Known as Phytoestrogens. (Sabah, 2021)

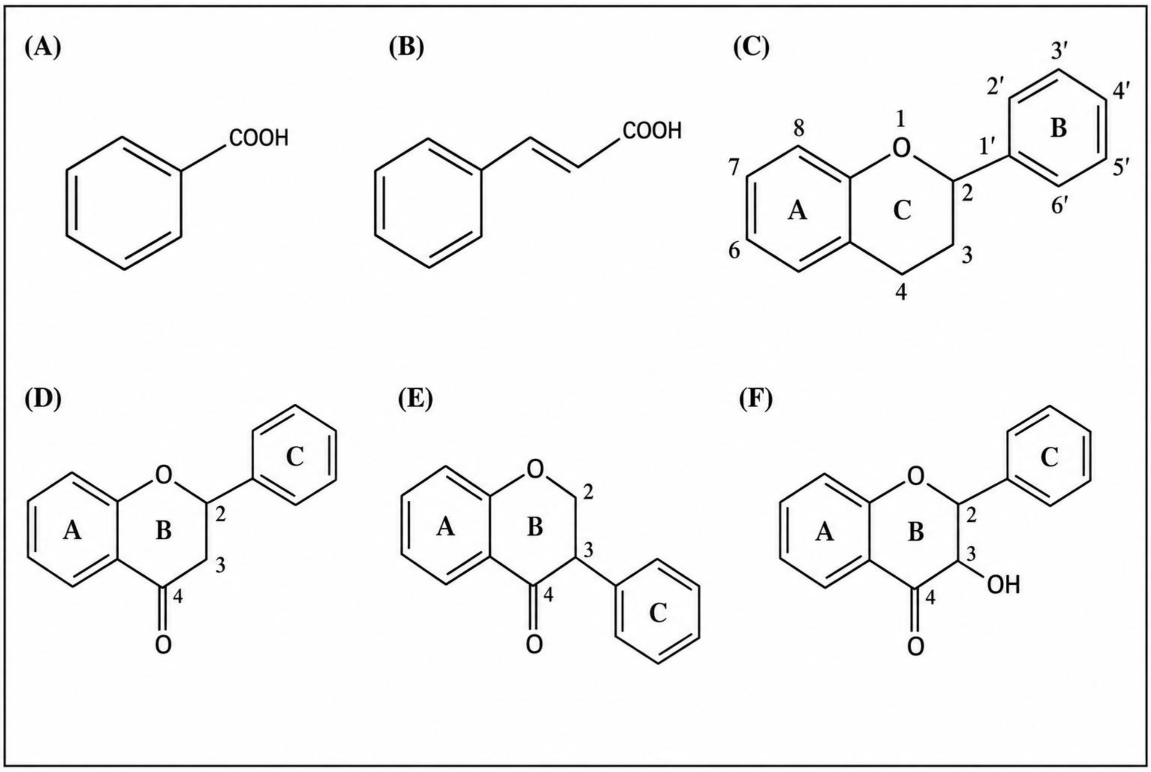


Figure 1. **Basic structural frameworks of plant phenolic compounds. Benzoic acid and cinnamic acid represent the principal hydroxybenzoic and hydroxycinnamic acid backbones, respectively, while flavan, flavone, isoflavone, and flavonol illustrate the major flavonoid subclasses derived from the C6–C3–C6 carbon skeleton**

3.4: Flavonols:

Flavonols, also known as flavan-3-ols, are the most complex class of flavonoids, occur as simple monomers and also as oligomers or polymer. Flavan -3-ols are characterized by a hydroxyl group at the 3 position.(Albuquerque *et al*.,2021)They are the building blocks of proanthocyanins (Fig 1). These compounds are abundant in a variety of vegetables and fruits such as onions, turnips, lettuce, tomatoes, apples, grapes and berries, in addition to their presence in herbs. It has broad health benefits, acts as an antioxidant and reduces the risk of vascular disease. (Sabah, 2021).

3.5: Anthocyanin:

They are water-soluble pigments found in the sap of the neonate cells and excreted by the secondary metabolism of plants. They give fruits, vegetables, flowers and leaves a multi-graded color from orange to Blue. Aglycone anthocyanins are referred to as anthocyanidins. While 17 natural anthocyanidins exist in nature, the most common species include: cyanidin, delphinidin, petunidin, peonidin, and malvidin.(Albuquerque *et al*.,2021).Anthocyanins possess beneficial health properties and have been widely used as natural colorants, primarily within the food industry.

3.6: Lignans and lignin:

Lignin, a significant plant polymer that reinforces cell walls by forming a matrix around cellulose microfibrils, is an important example of an untapped resources for aromatic material (Fif 2). The most effective method found for making these useful products more accessible is through the action of wood-rotting fungi. Lignin itself is created through the process of phenolic oxidative coupling of hydroxycinnamoyl alcohol monomers, a reaction facilitated by peroxidase enzyme. Lignans are organic compounds formed when the side-chain carbons of two phenylpropane derivatives link together. While many of these compounds demonstrate properties that inhibit cell growth (cytostatic) and cell division (antimitotic)—their most widely known bioactivity—only hemisynthetic derivatives of podophyllotoxin (extracted from the rhizomes of the American mandrake plant, *Podophyllum peltatum)* have been explored for therapeutic use. (Asif, 2015).

3.7: Stilbenes:

Stilbenes are natural phenolic compounds characterized by a C6–C2–C6 chemical structure, which features two benzene rings connected by a central double bond. The specific arrangement of this double bond classifies them into different isomers, typically cis and trans configurations. Generally, the biological activity of a specific stilbene is reduced when its isomerization type changes. There are currently more than 400 known stilbenes. Resveratrol is one of the most known stilbene.(Albuquerque *et al*.,2021). Stilbenes act primarily as phytoalexins in plants, functioning as a natural defense against pathogens and environmental stressors. These compounds also serve as allelochemicals (chemical signals in plant-plant interactions) and have significant applications in various industries. Industrially, stilbenes are used to produce scintillators, dyes, phosphors, luminescence sources, dye lasers, and optical brighteners. They are also widely utilized in the pharmaceutical, food, and cosmetic sectors for their beneficial properties, such as antioxidant, anti-inflammatory, and anti-aging effects. (Chong *et al*., 2009)

3.8: Tannins:

Tannins are large, water-soluble polyphenol compounds that primarily function by binding to proteins, although they also interact with other organic molecules like saponins, nucleic acids, alkaloids, and various polysaccharides. With a molecular weight generally ranging from 500 to 3000 Da, they remain soluble in water under typical temperature conditions (20–35 °C), with the exception of some highly complex structures. Within plants, tannins are strategically compartmentalized within vacuoles, a mechanism that prevents them from interfering with the plant's own cellular metabolism (Fig 2). Plant secondary metabolites, which include various phenolic compounds such as caric acid, are a class of compounds that feature both condensed and hydrolysable tannins, each performing distinct biological functions. Hydrolysable tannins are further categorized structurally into gallotannins and ellagitannins, which are derived from gallic acid. Condensed tannins are composed of procyanidin and prodelphinidin monomers. Their accumulation within plant cells is notable for playing a protective role against herbivore and insect attacks. (Iqbal and Poor, 2025).

3.9: Biosynthesis of Phenolic compounds

Phenolic compounds are a major group of secondary metabolites that are widely found in plants. (Santos-Sánchez *et al*., 2019) These compounds mainly form through the shikimate pathway, which operates in both higher plants and microorganisms. (Santos-Sánchez *et al*., 2019) Phenolics belong to the class of secondary aromatic metabolites and are produced either through the shikimate/phenylpropanoid route or the polyketide acetate/malonate pathway (Kumar *et al*., 2023). In plants, these compounds originate from the shikimic acid pathway or from the pentose phosphate pathway, both of which contribute to phenylpropanoid metabolism (Table 1). Basic metabolic processes like and the pentose pathway supply important molecules like PEP and E-4-P, which start the production of PC (Zagoskina *et al*., 2023). Both Phosphoenolpyruvate and E4P generate shikimic acid by shikimate pathway (Kumar *et al*., 2023). Amino acids including phenylalanine, tyrosine, and tryptophan act as key precursors, for the formation of many secondary metabolites (Kumar *et al*., 2023). The shikimate pathway has particular characteristics that occur only in bacteria, fungi, and plants.The 7 steps of this pathway are illuminated the compounds formed in this pathway forefather of P compounds (Santos-Sánchez *et al*., 2019)

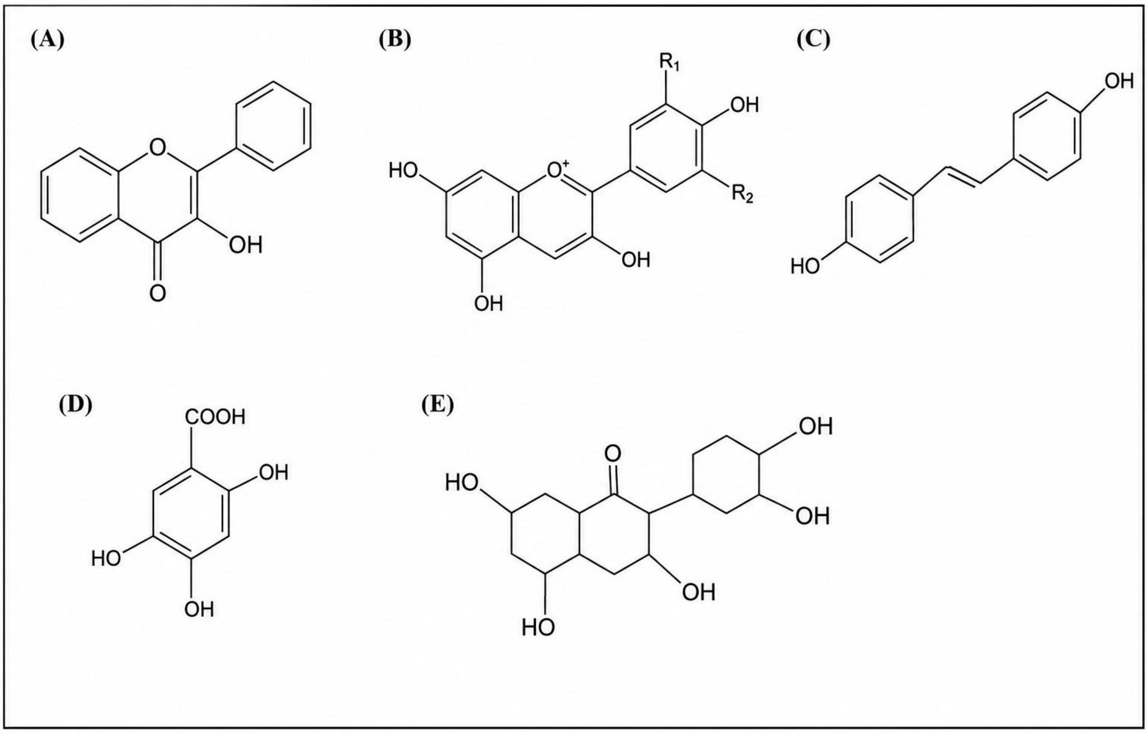


Figure 2. **Representative chemical structures of selected plant-derived polyphenolic compounds.** (A) **Flavonol skeleton,** (B) **Anthocyanidin (flavylium cation) skeleton,** (C) **Stilbene (resveratrol-type) skeleton,** (D) **Gallic acid (3,4,5-trihydroxybenzoic acid), and** (E) **Triterpenoid skeleton.**

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3.10: **Shikimate Pathway**

The name of this route takes from shikimic acid, which associated with formation of amino acids and Phenolic compounds. (Zagoskina *et al*., 2023) SHK acid also called by the name of flower shikimi, through which it was build. SHK route made up of 7 reaction steps start by PEP with the help of glycolytic route and D-E4P by the PP cycle to form 3DAHP. The 7 enzymes that perform the route are called Shikimate-k, 5-enolpyruvyl-S3PS, 3DAHPS, 3DHQS,3(DHQ\SDH) and CS. (Santos-Sánchez *et al*., 2019)

Table 1. Major classes of plant phenolic compounds, their primary dietary sources, and biological properties

.**Phenolic compound**	**Primary sources**	**Properties**	**Ref.**
Hydroxybenezoic acids	Fruits, Nuts Vegetables, grains , herbs and spices	Anti-fungal, antialgal, and antimicrobial	(Bhattacharya *et al*., 2010)
Hydroxycinnamic acids	Beverages, cereals, grains , fruits and vegetables	Photoprotective, Antioxidant, antimicrobial,	(Bi *et al.*, 2014)
Flavones	Leafy green vegetables, orange, tea and wheat sprouts	Anti-allergic, hepatoprotective, and anticancerous	(Durazzo *et al.*, 2019)
Isoflavones	Legumes, soybeans, nuts and coffee	Neuroprotective, and phytoestrogenic	(Durazzo *et al.*, 2019)
Flavanols	Berries, leafy green vegetables, and capers.	Cardioprotective, antiviral and anti-inflammatory properties	(Durazzo *et al.*, 2019)
Anthocyanins	Apples, pomegranates, cabbage, sweet potatoes, and raddish	Anti-diabetic effects, cardiovascular and Anti-cancerous activities.	(Durazzo *et al.*,2019)
Tannins	Cacoa, barley, Kola nuts, and beers	Antioxidant, anti-inflammatory and wound healing properties.	(Caleja *et al.*, 2017)
Stilbenes	Pine tree, mulberry, grapes, and peanuts.	Anti-cancerous, Antimicrobial and neuroprotective	(Durazzo *et al.*, 2019)
Lignans	Flaxseed, grains , nuts fruits and beverages	Hormones modulating, cardio protective and anti-microbial	(Mark *et al.*,2019)

Primary metabolic processes like EMP and the PP pathway deliver molecules PEP and E4P which begin the formation of phenolic compounds. (Kumar *et al*., 2023) Both compounds combine to form shikimic acid through the shikimate P. (Kumar *et al*., 2023) DAHP drops Pi and going through aldolization changed into 3-DHQ) (Santos-Sánchez *et al*., 2019) This is then desicate to form 3- DHS that have dual C. By the action of chemical processes DHS can be converted into protocatechuic acid or gallic acid C6–C1. DHS do redox reaction with reduced NADPH. In next step by operation of Shi acid with ATP by the help of Sk to produce shikimate-3-phosphate (S3P).By the insertion of phosphoenolpyruvate with S3P by the help of enzyme EPSPS creates 5-enolpyruvylshikimate-3-phosphate (EPSP).In the final step of S Pathway CS converts into chorismic acid (CHA. Chorismic acid is the end of S route is a major branching point, giving rise to L-phenylalanine , L-tyrosine , and L-tryptophan (Santos-Sánchez *et al*., 2019) In addition, shikimic acid can be converted into gallic acid with the help of the enzyme shikimate dehydrogenase (SDH) (Kumar *et al*., 2023)

3.11: Phenylpropanoid Pathway

The motive of shikimic acid is to distribute amino acid L-phenylalanine (L-Phe) and L-Tyr.By the removal of amino group of (L-Phe) with the help of enzyme phenylalanine ammonia-lyase (PAL) this transformed into trans-cinnamic acid. That reaction is considered the starting point in the phenylpropanoid pathway. Trans-cinnamic acid is think of the initial PC formed in plant cells connect aromatic amino acid metabolism with phenolic biosynthesis. Another enzyme, tyrosine ammonia-lyase (TAL), can convert the amino acid L-tyrosine (L-Tyr) into trans-cinnamic acid as well. (Zagoskina *et al*., 2023)

In monocot plants, the PAL enzyme can act on both L-phenylalanine and L-tyrosine, functioning as a dual-purpose enzyme, although it works more slowly with tyrosine. (Zagoskina *et al*., 2023)Trans-cinnamic acid then undergoes several hydroxylation reactions, forming different hydroxycinnamic acids including caffeic, ferulic, and chlorogenic acids. These intermediate acids rarely remain in their free form because they quickly move into additional reactions. Depending on the pathway branch, these compounds may undergo Beta-ox to form HB acids, be reduced to create cinnamyl Al involved in lignin development, or be transformed into esters such as chlorogenic acid. They may also be converted into coumarins and other phenolic derivatives. All these transformations contribute to the formation of the major phenylpropanoid compounds, which form the core of natural phenolic biosynthesis in plants. (Zagoskina *et al*., 2023).

3.12: Enzymes Involved in Phenolic Biosynthesis

The shikimate pathway relies on seven major enzymes to carry out its reactions, including 3-deoxy-D-arabino-heptulosonate-7-phosphate synthase (DAHPS), 3-dehydroquinate synthase (DHQS), 3-dehydroquinate dehydratase/shikimate dehydrogenase (DHQ/SDH), shikimate kinase (SK), 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), and chorismate synthase (CS) (Santos-Sánchez *et al*., 2019) The obtained phenylalanine is transformed into key acids coumaric, CA , and F acids through the enzymatic affair of PAL,C4H, and 4CL. (Kumar *et al*., 2023). The shikimic acid play role in the formation of gallic acid with the help of enzyme shikimate dehydrogenase (SDH) (Kumar *et al*., 2023). Formed gallic acid change into GG with the help of UGT which helps to generate tannins such as gallotannins and ellagitannins (Kumar *et al*., 2023). The development of Nar-Chal occured by the reaction of ρ-Cou-CoA with 3 Mal-CoA molecules with the help of chalcone synthase (CHS) (Kumar *et al*., 2023). The compound Nar-Chal is then changed into naringenin through the activity of chalcone isomerase (CHI) and then into DHK (Kumar *et al*., 2023). DHK split for formation of flavanones, flavanols, and anthocyanins (Kumar *et al*., 2023).

3.13: Aceto-Malonate (Polyketide) Pathway:

The aceto-malonate pathway is another key route in the formation of PC. Within the higher plants, this pathway combine with the PP pathway is important for flavonoid production. In flavonoid structures, the B-ring arise from the shikimate pathway (via hydroxycinnamic acids), and the A-ring is arise by the aceto-malonate pathway. (Zagoskina *et al*., 2023) The ρ-Cou-CoA reacts with 3 Mal-CoA and act as beginning compounds and generate Chal. (Zagoskina *et al*., 2023) This step is created by the enzyme chalcone synthase (CHS), which is considered a important enzyme in flavonoid formation. (Zagoskina *et al*., 2023) Produced Chal naringenin is then changed into F naringenin by the help of CHI (Zagoskina *et al*., 2023) After going through oxidation of the ring of naringenin becomes the starting point for the formation of many flavonoid families, including flavan-3-ols, flavanones, flavones, anthocyanins,excluding chal and dihydro Chal (Zagoskina *et al*., 2023).

3.14: Phenolic compounds Biosynthesis in response to plant injury

Phenolic compounds can be found in varying amounts in fruits, vegetables, and cereals. Phenolic compounds are plant produced Secondary metabolites. Along with its high pharmacological value, it also exhibits other biological activities as the primary contributors to fruits and vegetables overall antioxidant capacity. Fresh-cut processing method causes a notable rise in antioxidant and phenolic content. Plant injury initiates the phenylpropanoid metabolic pathway, a major route responsible for the biosynthesis of phenolic acids, flavonoids, anthocyanins, and many other aromatic metabolites (Fig 3). The process begins with the shikimate pathway, which produces precursors such as shikimic acid and phenylalanine. Reactive oxygen species (ROS) play a major role as signaling molecules during wounding stress. (Hu et al., 2022).

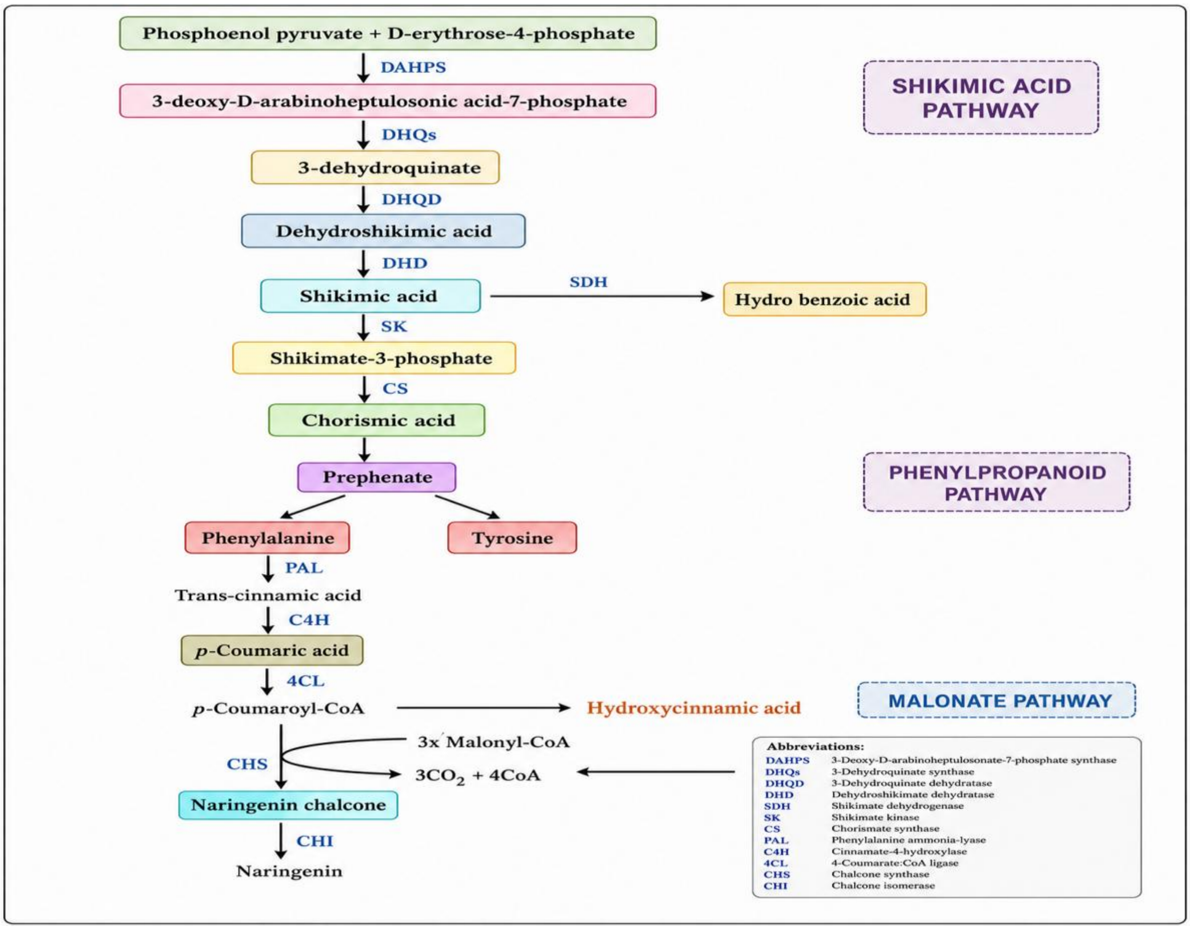

Figure 3. Biosynthetic pathways of major plant phenolic compounds derived from the shikimate and acetate–malonate pathways.

The general phenylpropanoid pathway contributes to many aromatic metabolites, such as coumarins, and is not limited to the biosynthesis of lignin or flavonoids. The first step in phenylpropanoid biosynthesis begins with the plant shikimate pathway. (Vogt, 2010)During chopping or cutting, fruit and vegetable tissues. This mechanical injury stimulates glycolysis and the pentose phosphate pathway, leading to increased production of erythrose-4-phosphate (E4P) and phosphoenolpyruvate (PEP). E4P and PEP are two intermediary and these are essential forerunner for shikimate pathway. They can eventually create the shikmic acid and phenylalanine.

The phenylalanine act as a chief base for the PPA pathway. Phenylalanine ammonia-lyase (PAL), cinnamate-4-hydroxylase (C4H), and 4-coumarate-CoA ligase (4CL) are important enzymes. Phenylalanine is altered into numerous phenolic acids as well as ferulic acid, caffeic acid and chlorogenic acid. At the beginning the catalyzed reactions take place for different branches of phenol containing compounds synthesis as well as the development of isoflavanones, flavonoids, anthocyanin and other phenolic metabolites.

These poly phenols are manufactured by the plants by using carbon obtain from the breakdown of glucose and PP pathway (Poly phenol pathway). Because there is higher level of phenolic compounds, anthocyanin, carotenoids, Vitamins and other antioxidant molecules in plant injured tissues (Fig 4). Injury triggered metabolism can be used as productive method to increase the manufacturing of functional compounds in fresh cut plants. Poly phenols such as Sinapic acid, inamic acid and caffeic acid have described to escalate the antioxidant properties in wounded plant tissues like broccoli. In addition to compounds such as quercetin, caffeic acid and vanillic acid act as a vital antioxidant donators in injured plant tissues (Hu *et al*., 2022).

When plants experience wounding stress, they release secondary metabolites. Numerous of these metabolites have antimicrobial, flavoring, and colorant properties in addition to preventing chronic diseases. Reactive oxygen species (ROS), ethylene (ET), and jasmonic acid (JA) are examples of signaling molecules that mediate the wound-induced production of secondary metabolites in plants. ROS are important signaling molecules that activate primary and secondary metabolism in response to wounds, while ET and JA are necessary to control ROS levels. (Jacobo-Velázquez et al., 2015).

3.15: Role of plant phenolic in abiotic stress:

Plants adapt and grow in response to environmental shifts by endlessly producing secondary metabolites. The type and amount of these metabolites, particularly phenolic compounds, are directly linked to the specific growth conditions and metabolic pathways activated by various environmental cues and stresses. (Chowdhary *et al.,* 2021).

Plants face various non-living stresses like drought, temperature shifts, salinity, alkalinity, and UV rays, alongside disease agents, all of which harm the plants. (Zafari *et al*., 2016). In plants, stress from biotic (pathogens) and abiotic (drought, salinity) factors boosts Reactive Oxygen Species (ROS), causing oxidative damage; plants counter this with enzymatic antioxidants (like SOD, CAT) and non-enzymatic ones (like flavonoids, vitamins) to detoxify ROS, which are also crucial signaling molecules for growth and adaptation, highlighting their dual role as harmful byproducts and essential regulators. (Dehghanian *et al*., 2022). Phenols protect plants from harmful oxidative stress, which damages essential biomolecules like DNA, proteins, and fats. (Zhang *et al*., 2021). Phenolic compounds act as scavengers; examples include phloretin, found in tea and apples, and pelargonidin, found in brown rice. (Kumar *et al*., 2023)

3.15.1: Stress of salt:

Salt stress causes water to leave plant cells due to osmotic disruption, shrinking the vacuoles and cytoplasm and dehydrating the cells. (Acosta-Motos *et al*., 2017). Salt stress triggers the phenylpropanoid biosynthetic pathway, which in turn enhances the biosynthesis of various phenolic compounds.(Valifard *et al* .,2024). Increased salinity leads to higher polyphenol content in various plant tissues.

3.15.2: Drought:

This mechanism helps plants mitigate the adverse effects of drought by acting as potent antioxidants that neutralize harmful reactive oxygen species (ROS) produced during stress, stabilizing cell membranes, and contributing to osmotic adjustment. The increased concentration of these compounds provides a vital defense mechanism, enhancing the plant's overall resilience.(Naikoo *et al*., 2019). Drought triggers increased production of flavonoids in plants, boosting their resistance to dry conditions. (Nakabayashi *et al*., 2019). Drought stress triggers the biosynthesis of phenolic compounds and flavonoids, ultimately resulting in increased plant yield. (Rezayian *et al*., 2014)

Drought conditions increase the activity of several genes responsible for producing beneficial plant compounds (polyphenols) in potato tubers. Specifically, the expression of genes and is significantly elevated when potatoes experience drought stress. This suggests that drought triggers a natural defense mechanism in the plant, potentially increasing the nutritional or stress-response compounds within the tuber itself. (André *et al*., 2009)

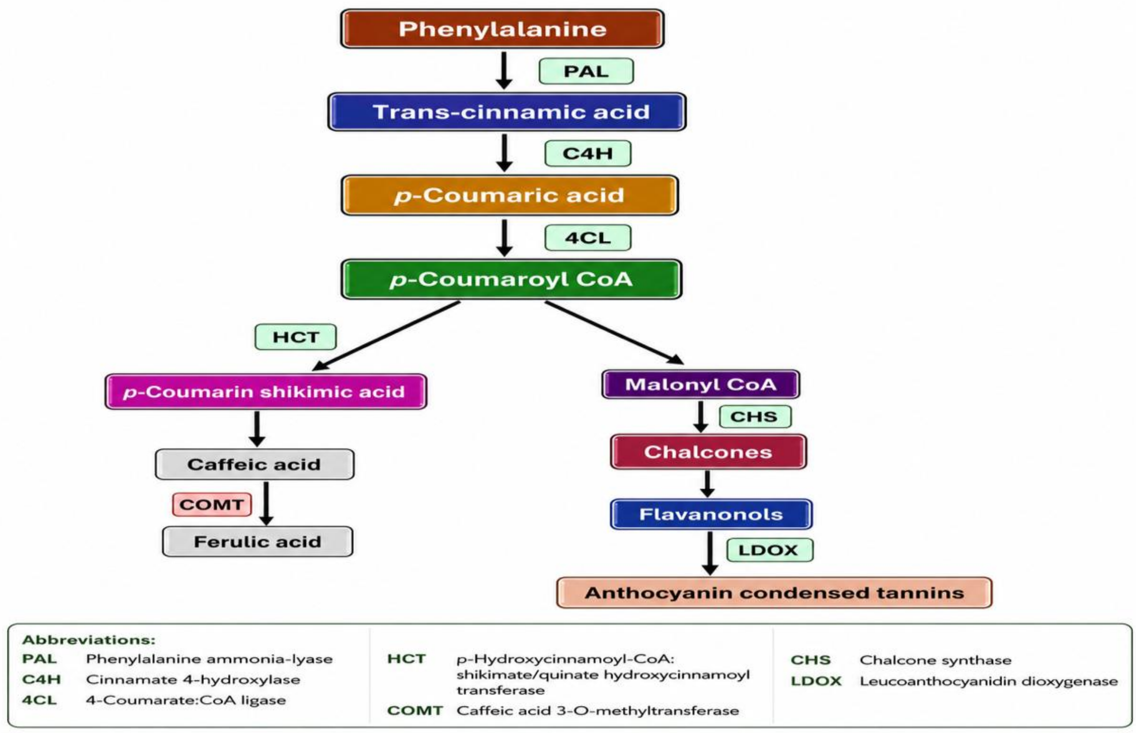

Figure 4. Biosynthetic pathways of phenolic secondary metabolites in plants.

3.15.4: Heavy metals:

Heavy metals represent a significant abiotic stress factor that hampers growth and physiological processes by inducing oxidative stress. (Naikoo *et al*., 2019)

These metals cause alterations in both metabolic and photosynthetic activities in plants. Metals such as lead, nickel, silver, cadmium, and arsenic increase the production of secondary metabolites, aiding plants in managing stress. (Rezayian *et al*., 2018). Heavy metals possess numerous electrons in their outer shell, which, under cellular conditions, react with native oxygen, resulting in highly reactive oxygen species.

Metal toxicity primarily stimulates the production of flavonoids, including anthocyanins and flavones. (D.; Elmasta *et al*., 2016).Activating the phenylpropanoid pathway leads to the synthesis of non-enzymatic compounds such as flavonoids, coumarins, and lignans. (Dutta *et al* .,2018).

3.15.5: UV radiation:

The quality of light and UV radiation also influence the synthesis of secondary metabolites in plants. (Castellarin *et al*., 2019). (Taïbi et al., 2016). UV radiation disrupts protein structure and induces changes in the genome that are detrimental, leading to the generation of reactive oxygen species in plants. . An increased concentration of secondary metabolites, such as alkaloids, terpenoids, and phenolic compounds, offers protection against UV radiation. (Bistgani *et al*., 2019)

There is a significant accumulation of phenolic compounds due to the introduction of genes involved in the flavonoid biosynthesis pathway under conditions of high light and UV radiation. Flavonoids serve as effective scavengers of reactive oxygen species, particularly those flavonoids that possess a catechol group in the B-ring of the flavonoid structure (e.g., quercetin derivatives). An excess of light or UV-B radiation stimulates the biosynthesis of dihydroxy B-ring-substituted flavonoids (e.g., luteolin derivatives) at the expense of other less effective flavonoids (e.g., kaempferol derivatives) (Del Valle *et al*., 2020)

The essential biosynthesis pathway genes for flavonoids, including CHS, CHI, FLS, DFR, FHT, FGT, and PAL, are activated by UV radiation. Concurrently, acylated anthocyanin absorb UV radiation and confer tolerance to UV stress in plants. (Zhang *et al*., 2018)

3.15.6: Other abiotic stress:

Abiotic factors, including nanoparticles, aerosols, temperature, and pesticides, also stimulate the production of phenolic compounds in plants. These phenolic compounds serve to protect plants from the phytotoxic impacts of such abiotic stresses. (Sharma *et al*., 2019). Additionally, plants generate and accumulate greater quantities of anthocyanins, flavonoids, flavanols, and phenolic acids in response to temperature stress, and these metabolites safeguard plant cells from damage inflicted by these stressors. (Ancillotti *et al*., 2015; Wang *et al*., 2019; Zlotek *et al*., 2015)

Furthermore, it has been observed that the plant *Festuca trachyphylla*, when subjected to heat stress, exhibits an increase in the biosynthesis of phenolic compounds, including 4-hydroxybenzoic acid, benzoic acid, caffeic acid, coumaric acid, cinnamic acid, gallic acid, homo-vanillic acid, ferulic acid, and salicylic acid. (Wang *et al*., 2019). The incorporation of these compounds enhances plant resistance by detoxifying reactive oxygen species generated under heat stress conditions. (Cingoz *et al*., 2016)

Moreover, the plant synthesizes additional phenolic compounds such as suberin or lignin, which fortify the plant cell wall and assist in preventing damage from chilling. (Naikoo *et al*., 2019)

3.16: Extraction of phenolic compound (PC)

Phenolic compounds are established in plants as aglyconesorglycosides, but depending on the solidity of the substance, they can also arise as matrix or free-bound molecules(Del Valle *et al*., 2020).Because most samples are complicated, the method of their preparation usually impact the result of entire separation process. Filtration, grinding, drying, homogenization, are a few typical sample preparation techniques used prior to extraction. In most situations, a hydrolysis step is also added to make it easier for chemicals to be released by selected context.

Although extraction of solvent methods are frequently familiar to produce raw elicit, aided extraction techniques, such as those that incorporate utilization of microwaves, UAE, and SFE have been frequently employed to obtain PC chemicals from plant substance (Alara *et al*.,2021). The speed at which phenolic compounds are extracted from plant samples can be impacted by inappropriate extraction methods and onestep extraction. Therefore, selecting the appropriate extraction method is crucial to extracting the intended phenolic compounds. (Dini *et al*., 2022).

3.16.1: Liquid Liquid separation / extraction (LLE):-

Investigators, investigate and evaluated the phenolic compound's extraction and processing from the numerous part of the plants, such as seed, leaves using a range of solvent.

They successfully elicited a variety of phenolic mixture from plants, depending upon the cost-efficient and clearness of this method of extraction, as well as the capability to utilize different solvent temperature, polarities and pH levels (Dini *et al.,* 2022).

The liquid liquid extraction supplies three divergent technique for phenolic compound's extraction; soxhlet extraction (SE), maceration and hydro distillation. The kind and polarity of the dissolving agent, their T (temperature) and duration of the extraction and ratio along with chemical and physical properties of the resources are essential aspect influencing these extraction (Zhang *et al* .,2018) . For example, ethanol and methanol along with ethyl acetate and acetone are constantly used in the phenolic compound's separation from citrus peel. Investigator applied soxhelt extraction and maceration system to analyze the complete flavonoids, and reduce tannins of phenolic compound in diverse solvents with different polarity (Zhang *et al*., 2022).

Generally, 1–30g of PCs can be pulled to utilize the LLE within 6–24 hours. The benefits of liquid liquid separation method contain genuine extraction processes and capability to extracts numerous phenolic compound (PCs) using organic solvent with different polarities; though the disadvantages encompass high solvent usage, extended extraction time low extraction production display to organic vapours and the potential degradation for the object compound during the process of extraction (Quitério *et al*., 2022).

3.16.2: Ultrasound assisted Extraction:-

Ultrasound assisted extraction is of the procedure that exposes capacity of obtaining plants from biologically active compound is the use of UA in the procedure of extraction (Hwabejire *et al*., 2023).due to its excellent and utilize lesser dissolving agent and T (time), UAE persists in accepted form while green separation . UAE is too suitable for compounds that are sensitive to temperature (Mehta *et al*., 2022).

Ultrasound assisted extraction is divided into direct UAE and indirect. UAEplaced directly onto the solvent mixture sample following the engulfment of an inert acoustical tool (sonotrode).Indirect UA radiation is applied to the sample-dissolving agent combination using an ultrasonic bath that can utilized at the same time for several specimen called indirect ultrasonic assisted extraction.(Ndudi *et al*., 2024). Ultrasound innovation has been successfully used to extract polyphenols, carotenoids, flavors, and polysaccharides from both whole plant and their byproducts (Del Valle *et al*., 2020).It is essential to control ultrasound Assisted Extraction connected parameters such as, duty cycle, time, frequency, power, solvent type, temperature, liquid solid ratio for the better achievement of extraction, several studies have research on the effect of those parameters the pair of separately and collectively on the separation of biologically active substances by derivatives of vegetables and fruits (Ahmed *et al*., 2021).

The bioactive compound within cells are liberate when cavitation, frequently known as sono operation, generate pores in the cell membrane (Fotsing Yannick Stéphane *et al*., 2022) Moreover the arrangements and breakdown of cavitation bubble include disorder and extend in the strain in fluent (liquid which spoils the extracellular wall and acid in the distribution of biologically active compound. Ultrasound not only makes the greater diffusivity of bioactive substances but also increases the water absorption of the pomace, consequently enhancing the solvent's availability for the extraction of the necessary bioactive compound (Egues *et al.*, 2021).

3.16.3: Microwave-assisted extraction (MAE):

Magnetism radiation with a frequency between 30 and 300 MHz is known as a microwave. They produce heat because of the stimulation of molecular movement, which disintegrates the cell wall and releases the mobile ingredients. Polar solvent molecules, for example water accelerate and enhance the effectiveness of phenolic chemical extraction because they have a higher dielectric constant and can absorb more energy than non- polar solvents. The two categories of MAE systems available for the separation of PCs are open and closed vessel.

Phenolic compounds are separated in an open vessel method at atmospheric pressure, but they are extracted in a closed vessel method at elevated pressure and temperature (Zhang et al., 2022). Another important benefit of this extraction method, which uses MAE to elicits PCs from fragrant plants utilize a variety of dissolving agent, is the capacity to swiftly and concurrently extract many compounds. MAE was conceivable through conclude that separation by microwave aid perhaps result in elevated separation products, compact separation periods, and lesser dissolving agent consumption by comparing these results with conventional reflux extraction. Additionally, a researcher investigated the antioxidative properties, flavonoid content and identity of flower and leaves of *Cassia angustigolia* (Pavlic et al., 2023).

Five methods were used to extract flavonoids: microwave, Soxhlet, reflux, condensation, marinating, and sonication extractions. Optimal choice were determined, through analyzing the overall flavonoid amount of various separation technique by the microwave extraction method (CalderonOliver et al., 2021). The extraction technique using the antioxidant activity and greatest quantity was found to be the one that produced the most flavonoids (Nwachukwu et al., 2024).

3.16.4: Supercritical fluid extraction (SFE):-

Supercritical fluid extraction (SFE) is an advanced procedure that offers various advantages better than traditional extraction technique. Supercritical fluid extraction usually appear ahead of high-performance liquid chromatography examine. (Usman *et al*., 2023). Low temperatures are one of those that gives a benefit when analyzing material that are heat sensitive. Further benefits include high selection, a clear decline in the quantity of the solvent required for extraction, and a small amount of substance required, smallest extraction time, mechanization capacity, both alternating hookup using majority chromatographic methods Gas chromatograph (GC) liquid chromatography (Emakpor *et al*.,2024). Due to its cheap, harmless and CO2 is commonly used in the supercritical fluid extraction for extraction process. However its direction is minimize than that of phenolic compound (PC), it doesn't the suitable dissolving agent when it occur to PC (Waseem *et al*., 2023). Scientist used carbon dioxide to separate phenolic compounds from *Psidium gujava L.*seeds which are part of the Myrtaceae family. Capability of SFE based upon various components. SFE are divided into 2 classification. (Dias *et al*., 2021).The first contains variables such as T (temperature), P(pressure), t(time), W(weight), S(sample), and strength that are pertinent to performing the extraction. The other includes matrix-related parameters such as analytic shape, uniformity, solubility, and desorption capability.

Furthermore, the SFE process is impacted by pH. Its variations could affect the pace at which the analyte is extracted from an aqueous phase as well as its extraction yield.SFE is widely used in the medicinal, food, and cosmeceuticals industries (Capuzzo *et al*., 2013). Supercritical fluid extraction can be familiarwith to recover bioactive substance from plant matter, especially those that traditional solvent extraction cannot separate.

3.17: Biochemical properties of Phenols

3.17.1: Anti-oxidant properties of phenlos

Polyphenols are vital in the methods of antioxidation. Those task by catch or offset reactive oxygen species which assist decrease the reacted injury. This reformer impose on unit with chemical structure. Reactive oxygen species are steady atoms identify before unstable electrons. Some excess of unstable molecules may outcome in strike on biomolecules like lipid bilayer, polypeptides and poly nucleotide playing a part to harmful effects like cell senescence, multiple disorders also the growth of tumor.

Specific intracellular proteins generate oxidants, specifically superoxide radicals and nitrogen monoxide like a feature of their enzymatic activity. Increased quantities either extended occurrence of those reactive species may elevate cellular stress at tissues whose may be trigger fabric trauma with lead into the appearance by situation. Including lesion, insulin resistance also high blood pressure. Hence, Analyzing it cellular signaling using who flavonoids quench harmful molecules remains super key. (Hu *et al*., 2024)

3.17.2: Polyphenols Phytochemicals effects look unstable molecules and oxidative species.

Below factors of physical stress, varied plant compounds notably enhance for fortifying plant. Adaptability, via of them phytochemicals traits during stressful. Specific potential of phenolic compounds towards stabilize. Cell damaging agents. Mine analysis reveals the definite phenolic substances. Like, plant pigment, luteola, trans- ferulic acid, sodium caffeate over various herbage (Rao *et al*., 2025). This flora provides similar to a rich sourced of natural products which preserve anti-natural and external obstacles. Comprising disease- causing agents, beams, drowning, metalloids with atmospheric conditions. Multiple kinds among them cellular products are detected. For instance carbolic acids, plant bases, essential oils, fatty acids with starches. Those molecules show a wide range of medicinal values. In people including oxidative stress reducer, carcinostatic, virucidal , glucose- lowering, cardio- beneficial together with brain protective impacts.plant derived compounds include specified through possessing a phenolic ring in addition to span around 8000 different structural arrangements. Multiple plant families such as Asteraceae, Rosaceae and Lamiaceae are identified as abundant providers of phenolics. (Merecz-Sadowska *et al.*, 2021)

Phenolic polymers spanning sourced from its sophisticated chemical architectures to their varied biological functions, are among the most widespread groups of metabolites in nature, found nearly everywhere. This type includes many naturally present phenolic, namely cinnamic acids, benzoic acids, flavonoids, pro anthocyanidins , coumarins, lignans , lignins and stilbenes.(Mafe et al., 2024)

3.18: Industrial Applications:

Phenolic compounds possess countless biotechnological applications across various industry. Their utilization is mostly assign to their antioxidant, antimicrobial, and coloring effects, among others, which are extremely research for food preservation by food and packaging industries, as well as in cosmetics and textile sectors. (Albuquerque *et al*., 2021)

3.18.1: Food industry:

Phenolic compounds are usually used in many food products because they naturally slow down oxidation and help control the growth of microbes. Foods that consist of a lot of fat like as meat, dairy items, and cooking oils spoil rapidly when exposed to air or light. Plant compounds like phenolic acids and flavonoids extend shelf life by stopping free radicals from causing spoilage. In this way, they protect the food from becoming rotten and help to maintain its freshness for a longer time. These compounds also impact the taste, aroma, and colour of drinks like tea, coffee, and wine. Their strong antioxidant effect has made them prominent as natural options to replace artificial preservatives, particularly in products aimed at health conscious consumers (Shahidi *et al*., 2015). With growing misgivings about artificial preservatives, there is increasing curiosity among researchers in discovering plant derived alternatives.

Among these natural options, phenolic compounds (PC) are considered highly valuable. They are generally recognized for two important roles:

1. Antioxidant effect: They prevent or slow the oxidation of fats, which is the chief reason of rancidity.
2. Antimicrobial effect: They suppress the growth of fungi, bacteria and other spoilage causing micrograms.

With these properties, phenolic compounds can act as natural preservatives and help to enlarge the shelf life of different foods. For example, when phenolic take away from the outer covering of *Litchi chinensis* was added to sheep meat nuggets, it displayed almost the same ability to control fat oxidations the synthetic antioxidant BHT (Das *et al*., 2016). Another study showed that phenolic obtained from the residues of *Olea europaea* L. that helped to reduce oxidation in frying oil at 180 °C during the preparation of French fries.

This extract protected oil based vitamins (tocopherols) for many hours, lowered the formation of harmful compounds like acrolein and hexanal, and distinctive BHT did not increase acrylamide formation. These findings clearly show why natural phenolic compounds (PC) are considered a better and safer choice compared to synthetic preservatives (Sordini *et al*., 2019).

3.18.2: Textile industry:

The textile industry is known for producing heavily contaminated waste water, principally due to the chemical dyes used during the colouring process. As well as polluting water, various synthetic dyes have been described to activate allergic reactions or skin irritation in sensitive individuals (Bonet-Aracil *et al*., 2016).Due to these issues, there is growing focus in using dyes made from plants, which suggest a more eco-friendly and safer option as opposed to chemical dyes.

Plant dyes, usually those rich in phenolic compounds, are getting attention because they break down easily in nature and are much reliable. For instance, dye made from the bark of oak (*Quercus* species) contains natural compounds like gallotannins, ellagitannins, and quercetin. When this dye is applicable to Tussah silk, it helps the fabric block harmful UV rays. Tea extracts either from red, black, or green tea show similar UV-protective effects when used on cotton. Another advantage of oak bark dye is that it can slow the growth of bacteria such as E. *coli* and S. *aureus*, making it a useful and environmentally friendly alternative to chemical dyes.(Jia *et al*., 2017).

3.18.3: Packaging industry:

Some phenolic compounds are being used in food packaging because they can fight oxidation and microbial growth (Zeng *et al*., 2019). Anthocyanin, for Example, are important for their bright colors and strong antioxidant effects. When combine into packaging films, they help to protect olive oil from spoiling (Wang *et al*., 2019). Their colour also changes with pH: red in acidic conditions (around pH 2) and green in alkaline conditions (around pH 11). This property makes it possible to make smart films that show how fresh food is spoil. For example, a film made of gelatin and polyvinyl alcohol with anthocyanin from mulberry (*Morus sp*.) can show the freshness of fish by changing the colour over time.

The changes from purple for fresh fish to brown after 18 hours and then to dark green after 24 hours, showing the fish is spoiled (Zeng *et al*., 2019). Phenolic acids, like gallic and caffeic acids, have also been added to chitosan-based films. These acids help to stop growth of *Bacillus subtilis* and *Staphylococcus aureus* while enhance the film's strength and its resistance to water vapour and oxygen (Wang et al., 2019). Tannins, which naturally bond with proteins, have been used in protein-based biofilms. These tannin-containing films not only fight *Escherichia coli* and Listeria *innocua* but also provide antioxidant protection, that making them useful for safer and more natural packaging. (Cano *et al*., 2020)

3.18.4: Cosmetic Industry:

The cosmetics industry has been transition toward using natural ingredients instead of artificial ones (Cherubim et al., 2020). Phenolic compounds are proving effective products for skin and hair (Soto et al., 2015). They help to protect the skin from the effects of sunlight, pollution, and aging. Compounds like ferulic acid, gallic acid, resveratrol, and polyphenols from green tea can calm inflammation, support collagen, and prevent dark spots. You can discover them in sunscreens, serums, anti-aging creams, and brightening products. They also help to keep the products stable, so they stay effective and last longer. (Działo *et al* , 2016) Hydroxycinnamic acids, including p-*hy*droxybenzoic, *p*-coumaric, incorporated and protocatechuic acids, have demonstrated significant stability over a prolonged period (6 months) when into a semi-solid base cream. They retain their anti-tyrosinase, anti-inflammatory, and antimicrobial properties, which makes them promising candidates for research as multifunctional cosmeceutical constituents. (Taofiq *et al*., 2019).

3.18.5: Pharmaceutical Industry:

Many phenolic compounds indicate therapeutic properties and have long been used in medicine. Salicylic acid, a simple phenolic compound, became the basis for aspirin, which is still one of the most generally used pain-relieving drugs. Current research show that polyphenols like as Quercetin, catechins, and curcumin may help to reduce inflammation, protect the heart, and limit the effects of oxidative stress related diseases. Phenolic compounds are also used as intermediates in drug synthesis and as stabilizers in pharmaceutical conceptualization to prevent the breakdown of active ingredients during storage. (Pandey *et al*., 2009).

Phenolic compounds (PC) are plant based molecules that Promote health and are known for playing an important role in minimizing disease risk like cancer, Alzheimer's disease, and diabetes (Caleja *et al*., 2017). The number of diabetes patients is increasing worldwide and may cross 400 million by 2030. One important factor behind this disease is oxidative stress, which occurs when reactive oxygen species (ROS) accumulate and body cannot control them. This imbalance leads to inflammation and disturbs insulin activity. Because phenolic compounds have strong antioxidant power, they help to lower ROS levels, stabilize the body's redox system, and protect pancreatic cells, making them useful in managing and preventing diabetes (Bahadoran *et al*., 2013).

3.19. Challenges and Future Perspectives of Phenolic Compounds

Challenges in the Sustainable Production of Phenolic Compounds

Despite the remarkable biological and industrial importance of phenolic compounds, several challenges hinder their sustainable production and large-scale commercial application. Among these, low bioavailability and poor stability are the most significant limitations.

Low Bioavailability:

Many phenolic compounds exhibit limited bioavailability due to their poor aqueous solubility, low permeability across biological membranes, and instability during gastrointestinal digestion, and extensive metabolism in the digestive tract and liver. Consequently, only a small proportion of the ingested phenolic compounds reaches systemic circulation in their biologically active form, thereby reducing their therapeutic efficacy. Improving the bioavailability of phenolics through advanced delivery systems, structural modification, Nano encapsulation, and formulation strategies remains a major research priority.

Poor Stability:

Phenolic compounds are highly susceptible to degradation during processing, storage, and transportation. Environmental factors such as temperature, light exposure, oxygen, moisture, and pH can induce oxidation, hydrolysis, and structural modifications, resulting in reduced biological activity and shortened shelf life. Therefore, developing effective preservation techniques, including microencapsulation, nanoencapsulation, controlled-release systems, and optimized storage conditions, is essential to maintain their chemical stability and functional properties.

Future Perspectives

Phenolic compounds possess a broad spectrum of pharmacological activities, including antioxidant, anti-inflammatory, antimicrobial, antiviral, anticancer, antidiabetic, and cardioprotective effects. Growing scientific evidence suggests that these naturally occurring phytochemicals have considerable potential for the prevention and management of numerous chronic diseases, including cardiovascular disorders, cancer, diabetes, neurodegenerative diseases, and inflammatory conditions.

Future research should focus on overcoming the limitations associated with the extraction, stability, bioavailability, and large-scale production of phenolic compounds. The integration of green extraction technologies, metabolic engineering, synthetic biology, plant cell culture, and biotechnological approaches offers promising opportunities for the sustainable production of high-value phenolics while minimizing environmental impacts. In addition, advances in nanotechnology and novel delivery systems are expected to enhance the stability, targeted delivery, and therapeutic efficacy of these bioactive compounds.

The demand for naturally derived functional ingredients is continuously increasing across the food, pharmaceutical, nutraceutical, cosmetic, textile, and agricultural industries. Phenolic compounds represent attractive alternatives to synthetic antioxidants and preservatives because of their safety, multifunctionality, and consumer acceptance. Their incorporation into functional foods, dietary supplements, active packaging materials, and cosmeceutical formulations is expected to expand significantly in the coming years.

Furthermore, the application of artificial intelligence, machine learning, metabolomics, and systems biology is anticipated to accelerate the discovery of novel phenolic compounds, optimize biosynthetic pathways, predict biological activities, and facilitate precision formulation of phenolic-rich products. Continued interdisciplinary research combining plant science, biotechnology, food technology, pharmacology, and computational biology will further unlock the full therapeutic and commercial potential of phenolic compounds, supporting their transition from laboratory research to sustainable industrial applications.

Author contribution: Conceptualization **AM**, Methodology **HAR**, Softwar **IA,** Formal analysis **AJ** and **ZT**, Investigation **UN**, Data curation **MI,** Writing original draft **AM, KF, SR** and **SK** writing review and editing **FF, MR, SQ**

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Declaration on the Use of Artificial Intelligence (AI):

The authors declare that any artificial intelligence (AI)-assisted technologies used during the preparation of this manuscript were employed solely to improve language, grammar, readability, or formatting. All scientific content, including the study design, data collection, analysis, interpretation of results, and conclusions, was conceived, verified, and approved by the authors. The authors accept full responsibility and accountability for the accuracy, originality, and integrity of the manuscript.

References:

Acosta-Motos, J. R., Ortuño, M. F., Bernal-Vicente, A., Diaz-Vivancos, P., Sanchez-Blanco, M. J., & Hernandez, J. A. (2017). Plant responses to salt stress: Adaptive mechanisms. *Agronomy*, *7*(1), 18. https://doi.org/10.3390/agronomy7010018

Alara, O. R., Abdurahman, N. H., & Ukaegbu, C. I. (2021). Extraction of phenolic compounds: A review. *Current Research in Food Science*, *4*, 200–214. https://doi.org/10.1016/j.crfs.2021.03.011

Albuquerque, B. R., Heleno, S. A., Oliveira, M. B. P. P., Barros, L., & Ferreira, I. C. F. R. (2021). Phenolic compounds: Current industrial applications, limitations and future challenges. *Food & Function*, *12*(1), 14–29. https://doi.org/10.1039/D0FO02324H

Ancillotti, C., Bogani, P., Biricolti, S., Calistri, E., Checchini, L., Ciofi, L., Gonnelli, C., & Del Bubba, M. (2015). Changes in polyphenol and sugar concentrations in wild type and genetically modified *Nicotiana langsdorffii* in response to water and heat stress. *Plant Physiology and Biochemistry*, *97*, 52–61. https://doi.org/10.1016/j.plaphy.2015.09.018

André, C. M., Schafleitner, R., Legay, S., Lefèvre, I., Aliaga, C. A. A., Nomberto, G., Hoffmann, L., Hausman, J. F., Larondelle, Y., & Evers, D. (2009). Gene expression changes related to the production of phenolic compounds in potato tubers grown under drought stress. *Phytochemistry*, *70*(9–10), 1107–1116. https://doi.org/10.1016/j.phytochem.2009.07.008

Asif, M. (2015). Chemistry and antioxidant activity of plants containing some phenolic compounds. *Chemistry International*, *1*(1), 35–52.

Babenko, L. M., Smirnov, O. E., Romanenko, K. O., Trunova, O. K., & Kosakivska, I. V. (2019). Phenolic compounds in plants: Biogenesis and functions. *The Ukrainian Biochemical Journal*, *91*(3), 5–18. https://doi.org/10.15407/ubj91.03.005

Bhattacharya, A., Sood, P., & Citovsky, V. (2010). The roles of plant phenolics in defence and communication during *Agrobacterium* and *Rhizobium* infection. *Molecular Plant Pathology, 11*(5), 705–719. https://doi.org/10.1111/j.1364-3703.2010.00625.x

Bi, X., Zhang, J., Chen, C., Zhang, D., Li, P., & Ma, F. (2014). Anthocyanin contributes more to hydrogen peroxide scavenging than other phenolics in apple peel. *Food Chemistry, 152*, 205–209. https://doi.org/10.1016/j.foodchem.2013.11.118

Bistgani, Z. E., Hashemi, M., DaCosta, M., Craker, L., Maggi, F., & Morshedloo, M. R. (2019). Effect of salinity stress on the physiological characteristics, phenolic compounds, and antioxidant activity of *Thymus vulgaris* L. and *Thymus daenensis* Celak. *Industrial Crops and Products, 135*, 311–320. https://doi.org/10.1016/j.indcrop.2019.04.058

Caleja, C., Ribeiro, A., Barreiro, M. F., & Ferreira, I. C. F. R. (2017). Phenolic compounds as nutraceuticals or functional food ingredients. *Current Pharmaceutical Design, 23*(19), 2787–2806. https://doi.org/10.2174/1381612823666170106114518

Castellarin, S. D., Pfeiffer, A., Sivilotti, P., Degan, M., Peterlunger, E., & Di Gaspero, G. (2019). Transcriptional regulation of anthocyanin biosynthesis in ripening grape berries under seasonal water deficit. *Plant, Cell & Environment, 30*(11), 1381–1399. https://doi.org/10.1111/j.1365-3040.2007.01716.x

Chen, S., Wang, X., Cheng, Y., Gao, H., & Chen, X. (2023). A review of classification, biosynthesis, biological activities and potential applications of flavonoids. *Molecules*, *28*(13), 4982. https://doi.org/10.3390/molecules28134982

Chen, S., Wu, F., Li, Y., Qian, Y., Pan, X., Li, F., Wang, Y., Wu, Z., Fu, C., & Lin, H. (2019). NtMYB4 and NtCHS1 are critical factors in the regulation of flavonoid biosynthesis and are involved in salinity responsiveness. *Frontiers in Plant Science, 10*, 178. https://doi.org/10.3389/fpls.2019.00178

Chong, J., Poutaraud, A., & Hugueney, P. (2009). Metabolism and roles of stilbenes in plants. *Plant Science, 177*(3), 143–155. https://doi.org/10.1016/j.plantsci.2009.05.012

Chowdhary, V., Alooparampil, S., Pandya, R. V., & Tank, J. G. (2021). Physiological function of phenolic compounds in plant defense systems. In *Phenolic Compounds: Chemistry, Synthesis, Diversity, Non-Conventional Industrial, Pharmaceutical and Therapeutic Applications*. Intech Open. https://doi.org/10.5772/intechopen.96695

Cingoz, G. S., & Gurel, E. (2016). Effects of salicylic acid on thermotolerance and cardenolide accumulation under high-temperature stress in *Digitalis trojana*. *Plant Physiology and Biochemistry, 105*, 145–149. https://doi.org/10.1016/j.plaphy.2016.04.041

Dehghanian, Z., Habibi, K., Dehghanian, M., Aliyar, S., Lajayer, B. A., Astatkie, T., Minkina, T., & Keswani, C. (2022). Reinforcing the bulwark: Unravelling the efficient applications of plant phenolics and tannins against environmental stresses. *Heliyon, 8*(4), e09094. https://doi.org/10.1016/j.heliyon.2022.e09094

Del Valle, J. C., Buide, M. L., Whittall, J. B., Valladares, F., & Narbona, E. (2020). UV radiation increases phenolic compound protection but decreases reproduction in *Silene littorea*. *PLoS ONE, 15*(4), e0231611. https://doi.org/10.1371/journal.pone.0231611

Dini, I., & Grumetto, L. (2022). Recent advances in natural polyphenol research. *Molecules, 27*(24), 8777. https://doi.org/10.3390/molecules27248777

Dutta, S., Mitra, M., Agarwal, P., Mahapatra, K., De, S., Sett, U., & Roy, S. (2018). Oxidative and genotoxic damages in plants in response to heavy metal stress and maintenance of genome stability. *Plant Signaling & Behavior, 13*(8), e1460048. https://doi.org/10.1080/15592324.2018.1460048

Durazzo, A., Lucarini, M., Souto, E. B., Cicala, C., Caiazzo, E., Izzo, A. A., and Santini, A. (2019). Polyphenols: A concise overview on the chemistry, occurrence, and human health. *Phytotherapy Research*, *33*(9), 2221-2243. https://doi.org/10.1002/ptr.6419

Działo, M., Mierziak, J., Korzun, U., Preisner, M., Szopa, J., & Kulma, A. (2016). The potential of plant phenolics in skin protection. *International Journal of Molecular Sciences*, *17*(2), 160. https://doi.org/10.3390/ijms17020160

Hu, W., Sarengaowa, Guan, Y., & Feng, K. (2022). Biosynthesis of phenolic compounds and antioxidant activity in fresh-cut fruits and vegetables. *Frontiers in Microbiology*, *13*, 906069. https://doi.org/10.3389/fmicb.2022.906069

Hu, Y., Zheng, Z., Zhai, D., Liang, P., Wang, Z., Jiang, C., & Liu, Q. (2024). A mini-review: Exploring the application prospects of the three major roles of antioxidants. *Journal of Molecular Structure*, *1304*, 137746. https://doi.org/10.1016/j.molstruc.2024.137746

Iqbal, N., and Poór, P. (2025). Plant protection by tannins depends on defence-related phytohormones. *Journal of Plant Growth Regulation*, *44*(1), 22–39. https://doi.org/10.1007/s00344-024-11341-3

Jacobo-Velázquez, D. A., González-Agüero, M., & Cisneros-Zevallos, L. (2015). Cross-talk between signaling pathways: The link between plant secondary metabolite production and wounding stress response. *Scientific Reports*, *5*, 8608. https://doi.org/10.1038/srep08608

Kováčik, J., Klejdus, B., Hedbavny, J., Štork, F., & Bačkor, M. (2009). Comparison of cadmium and copper effects on phenolic metabolism, mineral nutrients and stress-related parameters in *Matricaria chamomilla* plants. *Plant and Soil*, *320*(1–2), 231–242. https://doi.org/10.1007/s11104-008-9887-z

Kumar, K., Debnath, P., Singh, S., & Kumar, N. (2023). An overview of plant phenolics and their involvement in abiotic stress tolerance. *Stresses*, *3*(3), 570–585. https://doi.org/10.3390/stresses3030037

Kumar, S., Abedin, M. M., Singh, A. K., & Das, S. (2020). Role of phenolic compounds in plant defensive mechanisms. In A. Lone & N. Shuab (Eds.), *Plant Phenolics in Sustainable Agriculture* (pp. 517–532). Springer. https://doi.org/10.1007/978-981-15-4890-1_22

Merecz-Sadowska, A., Sitarek, P., Kucharska, E., Kowalczyk, T., Zajdel, K., Cegliński, T., & Zajdel, R. (2021). Antioxidant properties of plant-derived phenolic compounds and their effect on skin fibroblast cells. *Antioxidants*, *10*(5), 726. https://doi.org/10.3390/antiox10050726

Naikoo, M. I., Dar, M. I., Raghib, F., Jaleel, H., Ahmad, B., Raina, A., Khan, F. A., & Naushin, F. (2019). Role and regulation of plant phenolics in abiotic stress tolerance. In M. A. Khan et al. (Eds.), *Plant Signaling Molecules* (pp. 157–168). Elsevier. https://doi.org/10.1016/B978-0-12-816451-8.00010-5

Nakabayashi, R., Yonekura-Sakakibara, K., Urano, K., Suzuki, M., Yamada, Y., Nishizawa, T., Matsuda, F., Kojima, M., Sakakibara, H., Shinozaki, K., & Saito, K. (2014). Enhancement of oxidative and drought tolerance in *Arabidopsis* by overaccumulation of antioxidant flavonoids. *The Plant Journal*, *77*(3), 367–379. https://doi.org/10.1111/tpj.12388

Panche, A. N., Diwan, A. D., & Chandra, S. R. (2016). Flavonoids: An overview. *Journal of Nutritional Science*, *5*, e47. https://doi.org/10.1017/jns.2016.41

Pandey, K. B., & Rizvi, S. I. (2009). Plant polyphenols as dietary antioxidants in human health and disease. *Oxidative Medicine and Cellular Longevity*, *2*(5), 270–278. https://doi.org/10.4161/oxim.2.5.9498

Pratyusha, S. (2022). Phenolic compounds in plant development and defense. In *Plant Stress Physiology: Perspectives in Agriculture* (pp. 125–145). Springer. https://doi.org/10.1007/978-981-19-0140-9_6

Q.-W. Zhang, Lin, L.-G., & Ye, W.-C. (2018). Techniques for extraction and isolation of natural products: A comprehensive review. *Chinese Medicine*, *13*, 20. https://doi.org/10.1186/s13020-018-0177-x

Rao, M. J., & Zheng, B. (2025). The role of polyphenols in abiotic stress tolerance and their antioxidant properties to scavenge reactive oxygen species and free radicals. *Antioxidants, 14*(1), 74. https://doi.org/10.3390/antiox14010074

Rezayian, M., Niknam, V., & Ebrahimzadeh, H. (2018). Differential responses of phenolic compounds of *Brassica napus* under drought stress. *Iranian Journal of Plant Physiology, 8*, 2417–2425.

Roy, A., Khan, A., Ahmad, I., Alghamdi, S., Rajab, B. S., Babalghith, A. O., & Islam, M. R. (2022). Flavonoids: A bioactive compound from medicinal plants and its therapeutic applications. *BioMed Research International, 2022*, 5445291. https://doi.org/10.1155/2022/5445291

Sabah, F. S. (2021). Flavonoids, their types, chemistry and therapeutic efficacy. *Misan Journal of Academic Studies, 20*(41), 45–64.

Santos-Sánchez, N. F., Salas-Coronado, R., Hernández-Carlos, B., & Villanueva-Cañongo, C. (2019). Shikimic acid pathway in the biosynthesis of phenolic compounds. In M. Soto-Hernández, M. Palma-Tenango, & M. del Rosario Garcia-Mateos (Eds.), *Plant Physiological Aspects of Phenolic Compounds*. Springer. https://doi.org/10.5772/intechopen.83815

Shahidi, F., & Ambigaipalan, P. (2015). Phenolics and polyphenolics in foods, beverages and spices: Antioxidant activity and health effects—A review. *Journal of Functional Foods, 18*, 820–897. https://doi.org/10.1016/j.jff.2015.06.018

Sharma, A., Yuan, H., Kumar, V., Ramakrishnan, M., Kohli, S. K., Kaur, R., Thukral, A. K., Bhardwaj, R., & Zheng, B. (2019). Castasterone attenuates insecticide-induced phytotoxicity in mustard through modulation of antioxidant defense and phenolic metabolism. *Ecotoxicology and Environmental Safety, 179*, 50–61. https://doi.org/10.1016/j.ecoenv.2019.04.033

Taïbi, K., Taïbi, F., Ait Abderrahim, L., Ennajah, A., Belkhodja, M., & Mulet, J. M. (2016). Effect of salt stress on growth, chlorophyll content, lipid peroxidation and antioxidant defence systems in *Phaseolus vulgaris* L. *South African Journal of Botany, 105*, 306–312. https://doi.org/10.1016/j.sajb.2016.03.011

Valifard, M., Mohsenzadeh, S., Kholdebarin, B., & Rowshan, V. (2014). Effects of salt stress on volatile compounds, total phenolic content and antioxidant activities of *Salvia mirzayanii*. *South African Journal of Botany, 93*, 92–97. https://doi.org/10.1016/j.sajb.2014.04.004

Vogt, T. (2010). Phenylpropanoid biosynthesis. *Molecular Plant, 3*(1), 2–20. https://doi.org/10.1093/mp/ssp106

Wang, J., Yuan, B., & Huang, B. (2019). Differential heat-induced changes in phenolic acids associated with genotypic variations in heat tolerance for hard fescue. *Crop Science, 59*(2), 667–674. https://doi.org/10.2135/cropsci2018.07.0465

Wang, L., Shan, T., Xie, B., Ling, C., Shao, S., Jin, P., & Zheng, Y. (2019). Glycine betaine reduces chilling injury in peach fruit by enhancing phenolic and sugar metabolisms. *Food Chemistry, 272*, 530–538. https://doi.org/10.1016/j.foodchem.2018.08.077

Zafari, S., Sharifi, M., Ahmadian Chashmi, N., & Mur, L. A. J. (2016). Modulation of Pb-induced stress in *Prosopis* shoots through an interconnected network of signaling molecules, phenolic compounds and amino acids. *Plant Physiology and Biochemistry, 99*, 11–20. https://doi.org/10.1016/j.plaphy.2015.12.006

Zagoskina, N. V., Zubova, M. Y., Nechaeva, T. L., Kazantseva, V. V., Goncharuk, E. A., Katanskaya, V. M., Aksenova, M. A., & others. (2023). Polyphenols in plants: Structure, biosynthesis, abiotic stress regulation, and practical applications. *International Journal of Molecular Sciences, 24*(18), 13874. https://doi.org/10.3390/ijms241813874

Zhang, H., Troise, A. D., Qi, Y., Wu, G., Zhang, H., & Fogliano, V. (2021). Insoluble dietary fibre scavenges reactive carbonyl species under simulated physiological conditions: The key role of fibre-bound polyphenols. *Food Chemistry*, *349*, 129018. https://doi.org/10.1016/j.foodchem.2021.129018

Zhang, Q.-W., Lin, L.-G., & Ye, W.-C. (2018). Techniques for extraction and isolation of natural products: A comprehensive review. *Chinese Medicine*, *13*, 20. https://doi.org/10.1186/s13020-018-0177-x

Zhang, Y., Cai, P., Cheng, G., & Zhang, Y. (2022). A brief review of phenolic compounds identified from plants: Their extraction, analysis, and biological activity. *Natural Product Communications*, *17*(1). https://doi.org/10.1177/1934578X211069721

Złotek, U., Szymanowska, U., Baraniak, B., & Karaś, M. (2015). Antioxidant activity of polyphenols of adzuki bean (*Vigna angularis*) germinated under abiotic stress conditions. *Acta Scientiarum Polonorum Technologia Alimentaria*, *14*(1), 55–63. https://doi.org/10.17306/J.AFS.2015.1.6