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FRAGARIA × ANANASSA (STRAWBERRY): PHYTOCHEMICAL COMPOSITION, BIOLOGICAL ACTIVITIES, MECHANISMS OF ACTION, AND FUTURE PERSPECTIVES IN FUNCTIONAL FOOD AND NUTRITIONAL RESEARCH

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ABSTRACT

Fragaria × ananassa (garden strawberry) is one of the most extensively studied berry fruits due to its rich phytochemical composition and potential health-promoting properties. The fruit contains a diverse range of bioactive compounds, including anthocyanins, flavonoids, phenolic acids, ellagitannins, vitamins, organic acids, and volatile constituents that contribute to its nutritional and functional significance. These phytochemicals exhibit strong antioxidant, anti-inflammatory, cardioprotective, metabolic regulatory, neuroprotective, and gut microbiota–modulating activities through multiple molecular mechanisms. Strawberry bioactives influence important signaling pathways such as NF-κB, AMPK, nitric oxide-mediated vascular regulation, and endogenous antioxidant defense systems. In addition to its pharmacological relevance, Fragaria × ananassa serves as a valuable model for studying plant-derived bioactive compounds, food matrix interactions, and phytochemical variability. The phytochemical profile of strawberries is influenced by cultivar, environmental conditions, ripening stage, and post-harvest handling, resulting in considerable variation in biological activity. Although substantial evidence supports the beneficial effects of strawberry consumption, limitations remain regarding bioavailability, standardization of interventions, and the predominance of short-term experimental and clinical studies. Future research should focus on long-term human trials, precision nutrition approaches, gut microbiota interactions, and advanced delivery systems to improve the stability and bioavailability of strawberry phytochemicals. Overall, Fragaria × ananassa represents a chemically complex and biologically significant functional food with promising applications in nutrition, food science, and preventive health.

KEYWORDS: Fragaria × ananassa; Strawberry; Phytochemistry; Anthocyanins; Polyphenols; Antioxidant Activity; Anti-inflammatory Activity; Bioavailability; Functional Foods; Gut Microbiota; Nutraceuticals.

INTRODUCTION

Fragaria × ananassa (strawberry) is one of the most extensively studied berry fruits in contemporary food science and biomedical research, primarily due to its exceptional phytochemical complexity and functional relevance. Beyond its widespread consumption, strawberry has emerged as a model fruit system for investigating plant-derived bioactive compounds and their interactions within complex food matrices. Its chemical composition is characterized by a highly dynamic profile of primary metabolites and secondary plant compounds that collectively define its biological significance.

Among its constituents, strawberry is particularly enriched in phenolic compounds, including anthocyanins, flavonoids, and phenolic acids, which contribute to its high antioxidant capacity and biochemical reactivity. In addition, it contains essential micronutrients such as vitamin C and other minor bioactive components that further enhance its functional properties. The integrated presence of these compounds has positioned strawberry as a reference fruit in phytochemical and food chemistry investigations.[1,3,4]

Figure 1: Fresh fruit of Fragaria × ananassa (Garden Strawberry).[5]

From a biomedical perspective, growing experimental and clinical interest has focused on strawberry as a dietary matrix capable of influencing key physiological processes. Current evidence highlights its relevance in modulating oxidative stress-related pathways, inflammatory responses, and metabolic regulation, thereby strengthening its role in nutrition-linked disease research. This expanding body of literature has contributed to its recognition as a biologically active fruit with potential relevance in preventive health strategies.[1,2]

At the compositional level, Fragaria × ananassa exhibits significant variability in its bioactive profile, which is influenced by genetic background and environmental conditions. This inherent chemical plasticity not only affects its functional properties but also makes it a valuable system for studying structure–function relationships in plant-derived bioactives. Such variability further supports its continued use as a model fruit in advanced food chemistry and metabolomic research.[4]

Collectively, Fragaria × ananassa represents a chemically complex and biologically significant fruit that continues to attract strong multidisciplinary interest across food science, phytochemistry, and biomedical domains, particularly in the context of natural bioactive compounds and their functional implications.[1,2,4]

TAXONOMY AND BOTANICAL CHARACTERISTICS

Table no. 1: Taxonomical classification.[6,7]

Taxonomic Classification	
Kingdom	Plantae
Phylum	Magnoliophyta
Class	Angiospermae
Category	Fabids
Order	Rosales
Family	Rosaceae
Subfamily	Spiraeoideae
Genus	Fragaria
Species	Fragaria x ananassa

Table no. 2: Scientific name and synonyms.[6,7]

Scientific Name	Fragaria × ananassa Duchesne ex Weston
Synonyms	Fragaria chiloensis var. ananassa Duchesne ex Weston
	Fragaria vesca var. ananassa (Duchesne ex Weston) Aiton
	Potentilla × ananassa (Duchesne ex Weston) Mabb.

Table no. 3: Vernacular name.

Vernacular Names	
Hindi	स्ट्रॉबेरी (Strawberry)
Marathi	स्ट्रॉबेरी (Strawberry)
Gujarati	સ્ટ્રોબેરી (Strawberry)
Punjabi	ਸਟਰਾਬੇਰੀ (Strawberry)
Bengali	স্ট্রবেরি (Strawberry)
Tamil	ஸ்ட்ராபெர்ரி (Strawberry)
Telugu	స్ట్రాబెర్రీ (Strawberry)
Kannada	ಸ್ಟ್ರಾಬೆರಿ (Strawberry)
Malayalam	സ്ട്രോബെറി (Strawberry)
Urdu	اسٹرابیری (Strawberry)

Growth Habit

Fragaria × ananassa exhibits a perennial herbaceous growth habit characterized by a rosette-type architecture and a well-defined crown system. The crown serves as the central structural unit from which leaves, roots, and axillary buds originate. Seasonal developmental plasticity allows the plant to alternate between vegetative and reproductive phases, with vegetative propagation predominantly occurring through stolon (runner) formation arising from axillary meristems. This crown-based modular structure and runner-mediated clonal propagation are key determinants of plant architecture and ecological adaptability in cultivated strawberry systems.[8]

Leaves

The leaves of Fragaria × ananassa are trifoliate and arise in a basal rosette arrangement from the crown. These leaves represent a key morphological trait used in cultivar characterization and exhibit structural uniformity across cultivated types, although variation may occur among genotypes. Leaf morphology is an important diagnostic feature in distinguishing growth habits such as everbearing and non-everbearing types. The leaves contribute significantly to the overall vegetative architecture of the plant and are an integral component of its morphological identity.[9]

Flowers

The flowers of Fragaria × ananassa are hermaphroditic and typically arranged in cymose inflorescences. Floral development is regulated by environmental cues such as photoperiod and temperature, as well as genetic factors controlling flowering induction. The flowers contain numerous stamens and pistils, and their developmental regulation is closely associated with the balance between reproductive and vegetative growth pathways. This reproductive flexibility contributes to the perennial nature and cultivation adaptability of the species.[10]

Figure 2: Fresh fruit and flower of Fragaria × ananassa (Garden Strawberry).[11]

Encyclopaedia Britannica. (n.d.). Strawberry. Britannica. Retrieved June 10, 2026, from https://www.britannica.com/plant/strawberry

Fruit

The fruit of Fragaria × ananassa is classified as an aggregate accessory fruit, in which the edible portion is derived from an enlarged receptacle rather than the true ovary tissues. The true fruits, known as achenes, are distributed on the surface of the receptacle. During fruit development, a marked metabolic reconfiguration occurs between the receptacle and achenes, with distinct biochemical roles in each tissue. The receptacle accumulates sugars and organic acids, forming the fleshy edible structure, while the achenes function as seed-bearing units with independent metabolic activity.[12]

Distribution

Fragaria × ananassa is widely cultivated and naturalized across temperate regions of the world. According to Royal Botanic Gardens, Kew, the species is native to North America (including parts of British Columbia and the western United States) and has been extensively introduced and cultivated across Europe, Asia, Africa, and other regions. It is now globally distributed as a horticultural crop and is commonly grown in gardens and agricultural systems due to its wide adaptability to different climatic conditions.

Hybrid origin (important nomenclature note)

Hybrid formula

Fragaria chiloensis × Fragaria virginiana

Meaning of nomenclature

Fragaria → genus name

ananassa → species epithet (historical reference to pineapple-like aroma)

“×” → indicates interspecific hybrid origin.[13]

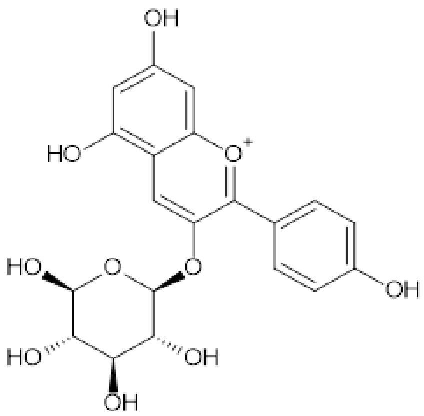
PHYTOCHEMISTRY OF FRAGARIA × ANANASSA

General Chemical Composition

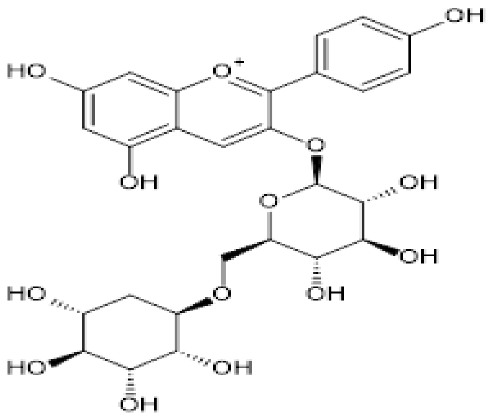
Fragaria × ananassa (garden strawberry) contains a wide variety of primary and secondary metabolites that contribute to its nutritional and medicinal value. The major phytochemical classes reported in strawberries include anthocyanins, flavonoids, phenolic acids, ellagitannins, tannins, sterols, glycosides, organic acids, carbohydrates, amino acids, vitamins, and volatile aroma compounds. The concentration and distribution of these compounds vary depending on the cultivar, environmental conditions, stage of ripening, and plant part analyzed. The rich phytochemical diversity of strawberry fruits and vegetative tissues is responsible for their antioxidant, protective, and physiological functions.[3]

Anthocyanins and Polyphenols

Anthocyanins are among the most abundant secondary metabolites present in ripe strawberry fruits and are primarily responsible for their characteristic bright red coloration. The major anthocyanins identified in strawberries are pelargonidin-3-glucoside, pelargonidin-3-rutinoside, and cyanidin derivatives. These compounds belong to the flavonoid group and exhibit strong antioxidant properties. Anthocyanin accumulation increases significantly during fruit ripening and contributes to fruit quality, appearance, and protection against oxidative damage. In addition to their role in pigmentation, anthocyanins help plants respond to environmental stress conditions and protect tissues from reactive oxygen species.[14]



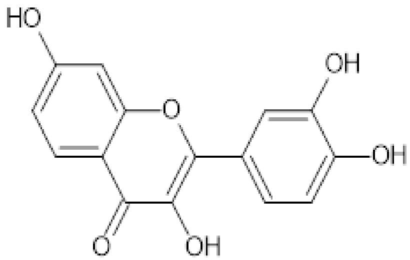
Pelargonidin 3 Glucoside



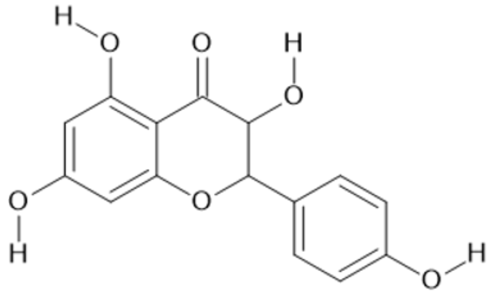
Pelargonidin-3-Rutinoside

Flavonoids

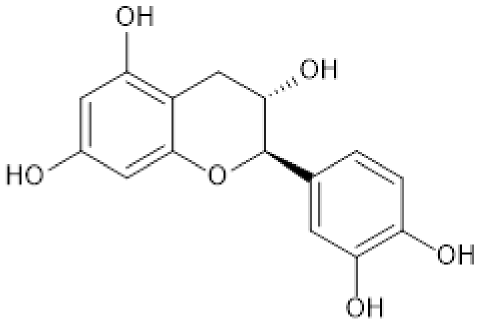
Flavonoids constitute an important group of polyphenolic compounds widely distributed throughout strawberry fruits, leaves, and flowers. Major flavonoids identified in strawberries include quercetin, kaempferol, catechin, epicatechin, and rutin. These compounds serve several biological functions, including protection against ultraviolet radiation, defense against pathogens, and regulation of plant growth. Flavonoids also contribute significantly to the antioxidant capacity of strawberries and play a role in maintaining cellular integrity under stress conditions. Their concentration is generally higher in leaves and outer fruit tissues compared to other plant parts.[15]



Quercetin



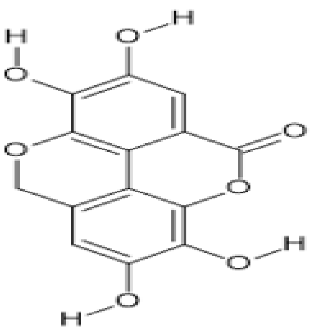
Kaempferol



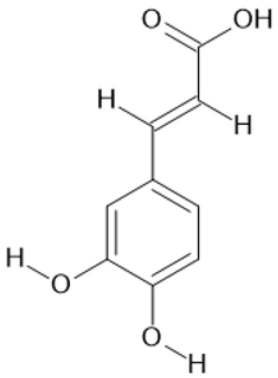
Catechin

Phenolic Compounds

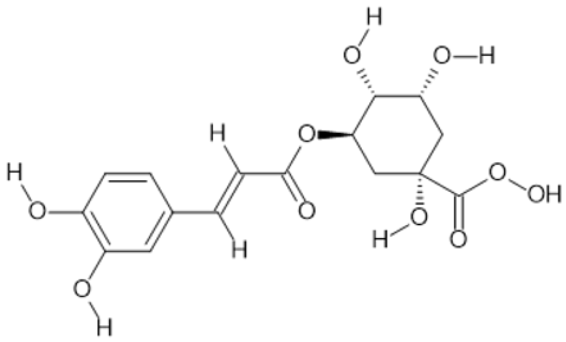
Phenolic compounds represent one of the largest groups of bioactive constituents in Fragaria × ananassa. Important phenolic acids reported include ellagic acid, caffeic acid, chlorogenic acid, ferulic acid, gallic acid, and p-coumaric acid. These compounds are involved in plant defense mechanisms and contribute to protection against environmental stress, microbial attack, and oxidative damage. Phenolics also participate in structural support and cellular signaling processes. Their antioxidant properties are considered one of the major factors responsible for the biological significance of strawberry fruits.[3,15]



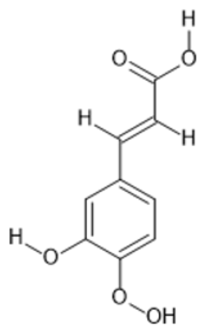
Ellagic Acid



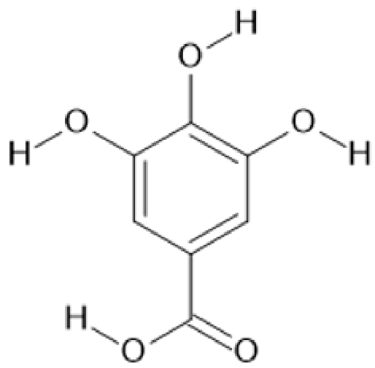
Caffeic Acid



Chlorogenic Acid



Ferulic Acid



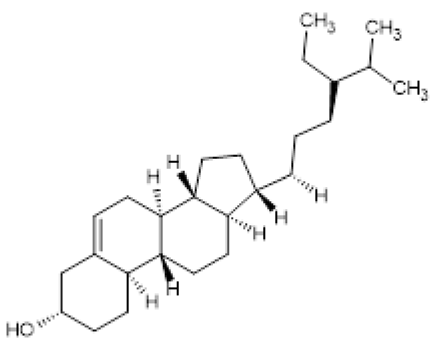
Gallic Acid

Tannins and Ellagitannins

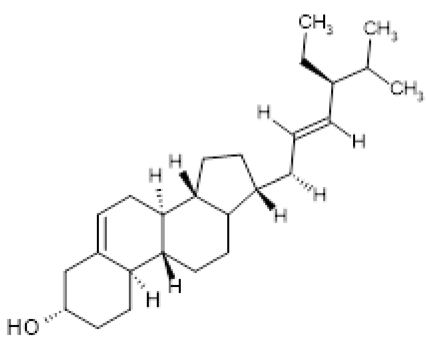
Strawberries contain considerable amounts of tannins, particularly hydrolysable tannins and ellagitannins. Major compounds include sanguiin H-6, agrimoniin, lambertianin C, and various ellagic acid derivatives. These metabolites are more abundant in leaves and unripe fruits than in fully ripened fruits. Tannins play an important role in plant defense by deterring herbivores and inhibiting microbial growth. They also contribute to the antioxidant activity of strawberries and serve as protective compounds against environmental stress factors.[15]

Sterols and Lipid Components

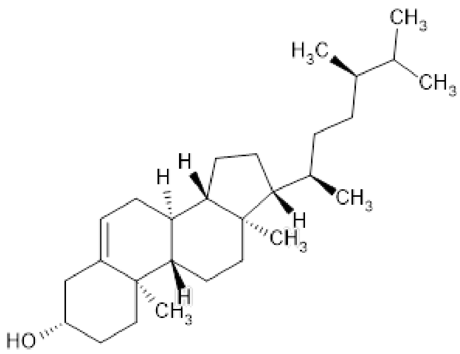
Plant sterols identified in strawberry tissues include β-sitosterol, stigmasterol, and campesterol. These compounds are primarily located in seeds, leaves, and stems, where they contribute to the structural stability of cellular membranes. Sterols are important for maintaining membrane fluidity, regulating permeability, and supporting normal cellular function. Although present in smaller quantities than polyphenolic compounds, they remain important constituents of the overall phytochemical profile of strawberries.[15]



β-sitosterol



Stigmasterol



Campesterol

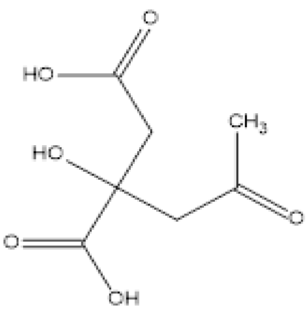
Glycosides and Carbohydrates

The fruits of Fragaria × ananassa contain various carbohydrates and glycosidic compounds that serve as energy sources and metabolic intermediates. The major sugars present are glucose, fructose, and sucrose, with fructose generally contributing most to the sweetness of ripe fruits. Pectin polysaccharides and trace amounts of sugar alcohols are also present. These compounds play important roles in osmotic regulation, fruit development, cellular metabolism, and maintenance of fruit texture and quality.[3]

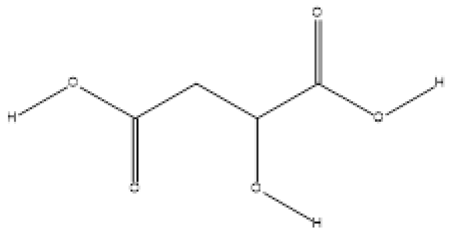
Organic Acids

Organic acids are important primary metabolites responsible for the characteristic sweet-tart flavor of strawberries. Citric acid is the predominant organic acid, followed by malic acid and smaller quantities of ascorbic acid (vitamin C).

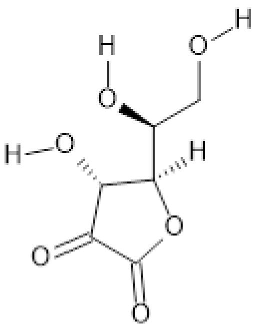
These compounds contribute to pH regulation, metabolic processes, and antioxidant protection within plant tissues. The balance between sugars and organic acids largely determines the sensory quality and consumer acceptance of strawberry fruits.[3]



Citric Acid



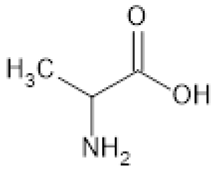
Malic Acid



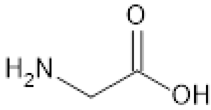
Ascorbic Acid (Vitamin C)

Amino Acids and Primary Metabolites

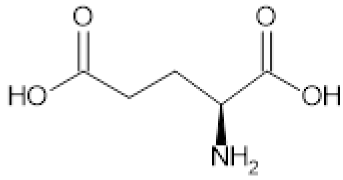
Strawberries contain several free amino acids, including alanine, glycine, glutamic acid, aspartic acid, and serine. These compounds are essential for protein synthesis, enzyme production, nitrogen metabolism, and various cellular processes. Although present in relatively low concentrations compared with carbohydrates and phenolics, amino acids contribute to the nutritional value and physiological functions of the fruit.[3]



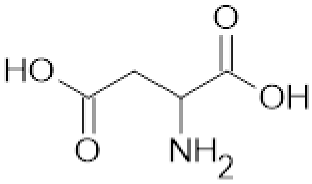
Alanine



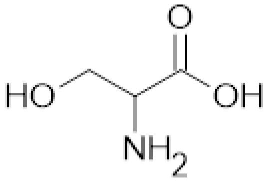
Glycine



Glutamic Acid



Aspartic Acid



Serine

Volatile Aroma Compounds

The distinctive aroma and flavor of strawberries arise from a complex mixture of volatile compounds. These include esters, aldehydes, alcohols, terpenes, furaneol, and mesifurane. Esters are particularly important because they impart the characteristic fruity aroma associated with ripe strawberries. The composition and concentration of volatile compounds vary among cultivars and change during fruit maturation and storage. These metabolites play ecological roles in attracting pollinators and seed dispersers while also contributing to consumer preference and market value.[15]

Distribution of Phytochemicals in Plant Parts

The distribution of phytochemicals within Fragaria × ananassa varies according to plant part. Fruits contain the highest concentrations of anthocyanins, sugars, organic acids, vitamin C, and many phenolic compounds. Leaves are particularly rich in flavonoids, tannins, and ellagitannins, whereas stems contain moderate amounts of sterols and polyphenols. Roots generally possess lower concentrations of secondary metabolites but contain structural compounds important for plant growth and development. Understanding this variation is important for phytochemical extraction, quality control, and industrial applications.[15]

Extraction and Solvent Dependence

The extraction of phytochemicals from strawberries depends greatly on solvent polarity. Water efficiently extracts sugars, glycosides, vitamin C, and organic acids, whereas ethanol and methanol are commonly used for extracting anthocyanins, flavonoids, phenolic acids, and tannins. Acetone is effective for recovering polyphenols, while non-polar solvents such as hexane preferentially extract lipids and sterols. Therefore, solvent selection is a critical factor influencing extraction yield and phytochemical composition.[3]

Chemical Standardization Overview

Quality assessment and standardization of strawberry extracts are commonly based on the determination of total phenolic content, total flavonoid content, total anthocyanin content, antioxidant activity, HPLC fingerprinting, and chromatographic profiling techniques. These analytical methods help ensure consistency, authenticity, and reproducibility in research studies and commercial formulations containing strawberry-derived ingredients.[3]

BIOAVAILABILITY

Anthocyanins and other berry polyphenols are poorly absorbed overall, with only small fractions reaching the bloodstream or urine. After eating berries, anthocyanins appear quickly in plasma (within 0.5–2 hours), suggesting partial absorption in the stomach and small intestine. However, absolute bioavailability is very low (often <1%), and most compounds are rapidly metabolized or excreted.

A significant portion of anthocyanins and other polyphenols reaches the colon, where gut microbiota break them down into smaller phenolic acids and other metabolites. These microbial products are often more absorbable than the original compounds and may contribute most of the biological effects.

Different classes behave differently:
Anthocyanins: Rapid but low absorption; extensively metabolized; major role of gut microbiota.

Proanthocyanidins: Poorly absorbed; largely converted in the colon to phenylvalerolactones and phenolic acids.

Flavonols (e.g., quercetin): Moderately better absorption than anthocyanins, but still variable.

Phenolic acids: More readily absorbed; often represent breakdown products of larger compounds.

Ellagitannins: Not absorbed directly; converted by microbiota into urolithins, which are more bioavailable and excreted in urine over longer periods.

Overall, gut microbiota plays a central role, converting large, poorly absorbed polyphenols into smaller metabolites that are absorbed and excreted. Because natural bioavailability is low, improving stability and absorption (e.g., liposomes, nanoparticles, solid dispersions) is considered important for enhancing their biological effects.[21]

MECHANISM OF ACTION OF FRAGARIA × ANANASSA

NF-κB inhibition (Fragaria × ananassa)

Strawberry extract inhibits activation of the NF-κB signaling pathway by suppressing UVB- and TPA-induced NF-κB transactivation in JB6 P+ mouse epidermal cells, leading to reduced inflammatory and proliferative signaling.[16]

AMPK activation

Strawberry bioactive compounds regulate energy metabolism by activating AMPK signaling pathway, which leads to increased fatty acid oxidation and reduced lipid accumulation, particularly observed in hepatocyte cell models.[17]

Antioxidant enzyme activation

strawberry plants (Fragaria × ananassa) activate their antioxidant defense system to counteract reactive oxygen species (ROS) accumulation. The key enzymatic responses include:

Superoxide dismutase (SOD)

First line of defense; converts superoxide radicals (O_2^-) into hydrogen peroxide (H_2O_2), reducing immediate oxidative damage.

Catalase (CAT)

Breaks down hydrogen peroxide into water and oxygen, preventing toxicity from H_2O_2 accumulation.

Glutathione peroxidase (GPx)

Reduces hydrogen peroxide and organic peroxides using glutathione, helping maintain cellular redox balance.[18]

Nitric Oxide Pathway

"Strawberry polyphenol extract has been shown to induce endothelium-dependent vasodilation via activation of the PI3K/Akt pathway, leading to endothelial nitric oxide synthase (eNOS) activation and increased nitric oxide (NO) production, suggesting a NO-mediated improvement in vascular function.[19]

PHARMACOLOGICAL ACTIVITIES OF FRAGARIA × ANANASSA

The biological activities of Fragaria × ananassa are mainly attributed to its rich content of anthocyanins, flavonoids, phenolic acids, ellagitannins, vitamin C, and other polyphenols. These compounds exert multifactorial molecular effects involving antioxidant defense, anti-inflammatory regulation, metabolic modulation, cardiovascular protection, and gut microbiota–mediated bioactivation. Overall, strawberry phytochemicals act through pleiotropic mechanisms rather than single-target pathways.[3,15]

Antioxidant

Strawberry polyphenols exert strong antioxidant activity by neutralizing reactive oxygen species (ROS) and inhibiting lipid peroxidation. Anthocyanins and flavonoids donate electrons or hydrogen atoms to stabilize free radicals, thereby preventing oxidative damage to DNA, proteins, and lipids. In addition, these compounds enhance endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), strengthening cellular antioxidant defense systems and maintaining redox homeostasis.[3]

Anti-inflammatory

Strawberry bioactive compounds reduce inflammation by inhibiting activation of NF-κB signaling pathways, which regulate inflammatory gene expression. This leads to decreased production of pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6. Additionally, polyphenols modulate cyclooxygenase (COX) and lipoxygenase (LOX) pathways, reducing synthesis of inflammatory mediators and eicosanoids. These actions contribute to suppression of chronic inflammatory responses.[20]

Cardiovascular Protective

Strawberry constituents improve cardiovascular health through multiple pathways, including enhancement of endothelial nitric oxide (NO) production, which promotes vasodilation and improves vascular function. They also inhibit LDL oxidation, reduce platelet aggregation, and improve lipid metabolism. These combined effects reduce atherosclerotic progression and improve overall vascular homeostasis.[20]

Metabolic Regulation

Strawberry polyphenols modulate glucose and lipid metabolism by influencing signaling pathways such as AMP-activated protein kinase (AMPK). This enhances glucose uptake, improves insulin sensitivity, and romotes fatty acid oxidation. As a result, strawberries contribute to regulation of energy metabolism and may reduce risk factors associated with obesity and type 2 diabetes.[15]

Gut Microbiota–Mediated Metabolism

A significant portion of strawberry ellagitannins and polyphenols are metabolized by gut microbiota into bioactive metabolites such as urolithins and phenolic acids. These metabolites exhibit enhanced bioavailability and biological activity compared to parent compounds. They contribute to systemic antioxidant and anti-inflammatory effects and link dietary intake with long-term physiological benefits.[21]

Neuroprotective

Strawberry polyphenols provide neuroprotective effects by reducing oxidative stress and neuroinflammation in neuronal tissues. They protect neuronal membranes, reduce lipid peroxidation, and support synaptic signaling. Some metabolites may cross the blood–brain barrier or act indirectly via systemic circulation, contributing to improved cognitive function and reduced risk of neurodegenerative disorders.[21]

SAFETY AND TOXICOLOGY OF FRAGARIA × ANANASSA

Strawberries (Fragaria × ananassa) are generally recognized as a safe dietary fruit with no reported toxicity at normal dietary intake levels. Human consumption studies consistently indicate that both fresh and processed strawberries are well tolerated, even at relatively high intakes of polyphenol-rich preparations.[22]

From a toxicological perspective, strawberries do not contain known naturally occurring toxic compounds at physiologically relevant levels. However, one of the primary concerns in modern food safety relates to agrochemical residues, as strawberries are among fruits most frequently associated with pesticide application due to their soft texture and susceptibility to fungal infection. Regulatory monitoring studies show that although residues may be detected, they typically remain within established safety limits when good agricultural practices are followed.[22]

Another safety consideration is allergic response, which is relatively rare but documented. Strawberry allergy is usually associated with pathogenesis-related proteins (e.g., Fra a proteins) and may cause mild oral allergy syndrome in sensitive individuals, particularly those with birch pollen allergy.[23]

Overall, strawberries are considered a low-risk functional food, and their health benefits significantly outweigh potential safety concerns when consumed as part of a normal diet.

LIMITATIONS OF CURRENT RESEARCH ON STRAWBERRY BIOACTIVES

Despite extensive research on Fragaria × ananassa, several limitations remain in the current scientific literature.A major limitation is that a significant proportion of studies are conducted in vitro or in animal models, which may not fully replicate human physiological conditions. As a result, translation of mechanistic findings (such as antioxidant or anti-inflammatory effects) into clinically meaningful outcomes remains partially uncertain.[24]

Another key issue is variability in strawberry cultivars, growing conditions, ripening stage, and post-harvest handling. These factors strongly influence polyphenol composition, leading to inconsistencies in experimental results across different studies.[1,3]

In addition, there is a lack of standardized dosing protocols in human intervention studies. Differences in intake form (fresh fruit, freeze-dried powder, juice, or extract) and polyphenol concentration make it difficult to compare outcomes directly.[24]

Most clinical trials are also of short duration, limiting conclusions about long-term cardiovascular, metabolic, or neuroprotective effects.[24]

Finally, individual differences in gut microbiota composition significantly affect the metabolism of strawberry polyphenols into bioactive compounds such as urolithins and phenolic acids. This inter-individual variability leads to different "metabotypes," influencing biological response and complicating interpretation of results.[25]

SYNERGISTIC EFFECTS OF STRAWBERRIES WITH OTHER FOODS

Strawberry bioactive compounds may exhibit synergistic or enhanced bioavailability effects when consumed with other dietary components.

One well-studied combination is strawberries with dairy products such as yogurt or milk. Dairy proteins, particularly casein, can bind polyphenols and influence their stability and release during digestion. Some studies suggest that fermented dairy matrices may enhance the stability of anthocyanins in the gastrointestinal tract, although effects on absorption can vary depending on formulation.

Dietary lipids (fats) may also enhance the absorption of certain polyphenol metabolites indirectly by improving micellar solubilization of lipophilic derivatives formed during digestion. This can potentially increase systemic availability of some phenolic compounds.

Additionally, co-consumption of strawberries with other polyphenol-rich fruits (e.g., blueberries, blackberries, grapes) may lead to additive or synergistic antioxidant effects due to complementary phytochemical profiles, including anthocyanins, flavonols, and ellagitannins. Such combinations may also influence gut microbiota composition more strongly than single fruit consumption.

Overall, food matrix interactions play a critical role in determining the bioaccessibility and biological effectiveness of strawberry phytochemicals.[26,27]

FUTURE PERSPECTIVES OF FRAGARIA × ANANASSA RESEARCH

Despite extensive progress in understanding the phytochemistry and biological activities of Fragaria × ananassa, several emerging areas warrant further investigation to fully translate its health potential into clinical and nutritional applications.Future research should prioritize well-designed long-term human clinical trials to confirm the cardiometabolic, neuroprotective, and anti-inflammatory effects of strawberry intake observed in in vitro and animal studies. Current evidence strongly supports beneficial outcomes on oxidative stress, vascular function, and metabolic regulation; however, most studies remain short-term or mechanistic in nature, limiting clinical extrapolation.[24,28]

A key future direction is the development of standardized strawberry-based interventions, including freeze-dried powders, extracts, and functional foods with defined polyphenol composition. Variability in cultivar type, ripening stage, and agricultural conditions significantly affects phytochemical content, making cross-study comparisons challenging and highlighting the need for chemical standardization protocols.[1,3]

Another important perspective involves advancing nutrigenomics and precision nutrition approaches, particularly in relation to inter-individual variability in response to strawberry polyphenols. Differences in gut microbiota composition strongly influence the conversion of ellagitannins and other phenolics into bioactive metabolites such as urolithins, suggesting that personalized dietary responses may play a critical role in health outcomes.[25]

In addition, future studies should explore food matrix interactions and bioavailability enhancement strategies, including encapsulation technologies, nanoformulations, and co-consumption effects with other dietary components. These approaches may significantly improve the stability and systemic availability of strawberry bioactives.[3,28]

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