

# One Fruit, Many Effects: Understanding the Biological, Nutritional, and Therapeutic Roles of *Malus domestica*

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## ABSTRACT

Apple (*Malus domestica*), belong to Rosaceae family; attract the world due to exceptional economic, nutritional, and medicinal significance. In India, apple cultivation is primarily concentrated in the Himalayan states Jammu and Kashmir, Himachal Pradesh, and Uttarakhand where climate and soil conditions support high-quality production. Beyond its role as a major horticultural crop and livelihood source, apples are valued for their rich phytochemical profile. Apples contain notable flavonoids such as quercetin, catechin, epicatechin, and anthocyanins, along with phenolic acids like chlorogenic and gallic acids. Triterpenoids such as ursolic acid and oleanolic acid further enhance their therapeutic potential. Additionally, dietary fiber especially pectin plays a crucial role in digestive health, lipid regulation, glycemic control, and modulation of the gut microbiota. The fruit also provides essential micronutrients such as potassium, vitamin C, and vitamin E, which synergistically support metabolic and immune functions. Modern pharmacological studies validate the traditional medicinal uses of apples. It plays a major part in preventing long-term illnesses like cancer, diabetes, heart disease, and neurological disorders. This review summarizes apple taxonomy, cultivation practices, phytochemical composition, production trends in India, and the extensive pharmacological activities associated with its bioactive constituents. The evidence highlights apples as a nutritionally and therapeutically valuable fruit with broad applications in promoting human health.

**Keywords:** Harvesting, *Malus domestica*, Pharmacological evaluation, Phytochemical composition, Taxonomy.

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## INTRODUCTION

Northern part of India especially Kashmir, Himachal Pradesh and Uttarakhand are the major states for total production. Apple is considered as fruit of choice among people across the world for its unique delicious taste (Oyenihi *et al.*, 2022). The apple is considered as a major crop for cultivators in term economic stand point of India. The apple of Kashmir persists its global

recognition in national and international markets (Patocka *et al.*, 2020).

Apples was first cultivated in South-Western Asia's Caucasus Mountains (Figure 1). Thereafter, during the era of Christianity it was spread to all Europe and Asia. The nutritional value of apple has given its global recognition. In the early 1865 British was cultivated in India at the Kullu valley of Himachal Pradesh. The market demand and climatic conditions spread the cultivation to the neighboring states like Jammu and Kashmir (Calvo-Castro *et al.*, 2022). The growth of apple depends on moderate soil, climate, slope (Mierczak *et al.*, 2024). Generally harvesting carried out within the months from September to November. Due to major processing from cultivation to marketing it provide jobs to over 60% of the population and are the main source of income for many people (Asma *et al.*, 2023).



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Worldwide 21,000 medicinally plant species are listed by the WHO. Approximately 2500 plant species from nearly 1000 genera are employed in India's traditional drug system, which represents the country's long history of using herbs and herbal treatments. Herbs and plants have long been utilized by various civilizations worldwide to treat a variety of illnesses and preserve health (Zhang *et al.*, 2023). Plants are the source of many medications used in today's healthcare system. The synthetic medication is known to be hazardous and occasionally requires significant medical care. Because of its effectiveness and seeming safety profile, herbalism has gained appeal recently throughout the world, even in affluent nations (Vasile *et al.*, 2021).

The phytochemicals are frequently created for various health issues, as demonstrated by scientific studies on medicinal plants (Perrone *et al.*, 2025). Total consumption of apple is largest one in most of the countries due to its available market place and huge number of cultivature. This is why a well-known phrase is there "an apple a day, keeps the doctor away". The apple is an wellknown nutritious food for the diseases like cancer, diabetes and associated cardiovascular diseases. It also reduce lipid oxidation, and exhibit hypocholesteromic activity. There are wide range of phytoconstituents flavanods namely quercetins and phenolic acids are present. It also contain large amount of fiber, which plays a vital role in its lipid-lowering capacities (Samid *et al.*, 2023). The current review described detailed taxonomical classification, cultivation and production, phytochemical and pharmacological investigation of apple.

### Search Strategy

Google Scholar was initially used for initial overview of existing review and to identifying highly cited papers, and tracing citation networks. The PubMed focused access to peer-reviewed studies on nutrition, metabolism, and therapeutic effects of Apple. The ScienceDirect and SpringerLink provide the articles in food science, plant biology, and pharmacology. Using these search engines in combination supports a rigorous, transparent, and well-substantiated narrative suitable paper for publication in the journal.

## REVIEW OF LITERATURE

### Plant Profile of Apple (Kumar *et al.*, 2022)

- **Botanical Name:** *Malus domestica*.
- **Family:** Rosaceae.
- **Plant Type:** Deciduous fruit tree.
- **Description:** Apple trees are medium-sized deciduous trees known for their sweet or tart edible fruit. They typically reach 4-12 M in height, with a spreading canopy and fragrant blossoms in shades of white to pink.

### Climate and Soil Requirements

- **Climate:** Temperate regions with cold winters for proper dormancy.
- **Soil:** Well-drained loamy soil, pH 6.0-7.0.
- **Sunlight:** Full sun (6-8 hr daily).

### Propagation

Commonly propagated through grafting; seeds do not produce true-to-type fruit.

### Harvesting

Harvest typically occurs in late summer to autumn, depending on the variety. Fruit should be firm, crisp, and fully colored.

### Cultivation and Collection

Apple (*Malus domestica*) cultivation requires careful management of soil, climate, and orchard practices. Apple trees do best in loamy soil that drains well and has a pH between 6.0 and 7.0. The land must be thoroughly plowed and leveled to ensure proper root development. Plantation usually done during late winter or early spring, with spacing of about 4-5 M depending on the variety and rootstock. Regular irrigation is essential, especially during the flowering and fruit-setting stages (Table 1). Pruning plays a crucial role in shaping the tree, improving air circulation, and maximizing fruit yield. The use of fertilizers containing nitrogen, phosphorus, and potassium are used based on soil condition to support healthy growth (Cicero *et al.*, 2017).

The collection or harvesting of apples typically takes place during late summer to autumn, depending on the variety. Fruits are picked by hand to prevent bruising and maintain quality. Apples are harvested when they reach their full color, optimum size, and proper firmness. After harvesting, the fruits are graded and sorted for market or processing use. For longer shelf life, apples are stored in cold storage units at temperatures between 0°C and 4°C (Shoji T *et al.*, 2017).

Apple cultivation is highly climate-dependent. Apples grow best in temperate climates where winters are cold and summers are moderately warm. Most apple varieties require 800 to 1500 hr of chilling below 7°C to break dormancy and ensure proper flowering and fruiting. During the growing season, temperatures around 21°C to 24°C are considered ideal. A frost-free spring is essential to protect blossoms from damage. Apples also require plenty of sunlight, usually 6-8 hr per day, to develop good color, flavor, and sugar content. Regions situated at altitudes between 1500 and 2700 M are particularly suitable for commercial apple cultivation due to their favorable climatic conditions (Liu *et al.*, 2019).

## Production in India

Apple (*Malus domestica*) production in India is concentrated in the Himalayan states where cool winters and adequate chilling hours favour high-quality fruit. Over the last five years (2019-2023), India's apple production has shown variability driven by weather events, orchard management practices, and changing market dynamics. Using FAO-derived national production data, India produced approximately 2.33 million tonnes in 2019, 2.32 million tonnes in 2020, a notable increase to 2.81 million tonnes in 2021, followed by a dip to 2.28 million tonnes in 2022, and a rebound to 2.88 million tonnes in 2023 (Angeli *et al.*, 2024).

This fluctuation reflects multiple factors. Climatic variation particularly winter chilling, spring frosts, and monsoon timing strongly influences flowering, fruit set and final yields. The dominant producer, Jammu and Kashmir (including Ladakh), contributes roughly 60-70% of national output, with Himachal Pradesh and Uttarakhand supplying most of the remainder. Growers face challenges such as outdated orchards, inconsistent irrigation, and limited cold-chain infrastructure, which together limit average productivity relative to global benchmarks (Oszmiański *et al.*, 2018).

Modernization to high-density plantation on dwarf rootstocks, drip irrigation, integrated pest management, and improved storage condition improve yields and fruit quality. For example, high-density orchards under good management can reach far higher yields than traditional systems, improving both farm-level income and marketable output. Government and industry initiatives to expand refrigerated transport and controlled-atmosphere storage are important for reducing post-harvest losses and increasing the availability of fresh apples in distant urban markets (Starowicz *et al.*, 2020).

Trade has also affected domestic production and prices. India imports apples (notably from Turkey and other suppliers) to meet demand for certain varieties and off-season supply; imports rose markedly in recent years. Conversely, limited export volumes reflect domestic consumption priorities and cold-chain constraints (Calbo-Castro *et al.*, 2022). Looking ahead, climate resilience (including development and adoption of low chill cultivars), investment in cold chain and processing, and wider adoption of modern orchard practices are critical to stabilising production. The five-year data illustrates both the sector's vulnerability to weather and its latent potential with the right policy support and technology adoption, India can enhance productivity while supporting millions of growers who depend on apple cultivation for their livelihoods (Table 2).

Apple production does more than determine yield and appearance; it directly shapes the phytoconstituent content of the fruit. Growing conditions, variety selection, and harvest timing influence the formation of bioactive compounds such as polyphenols and flavonoids, which contribute to the nutritional

and health benefits of apples. Recognizing this connection helps in developing production practices that enhance both fruit quality and its functional value (Asma *et al.*, 2023).

## Phytoconstituents

The diverse array of phyto-constituents found in apples, particularly polyphenols, flavonoids, triterpenoids, carotenoids, organic acids, pectins, and various volatile compounds. The unique combination of these bioactive components makes apples an important dietary source for promoting optimal health. The major phytochemicals in apples, distributed within different tissues (Table 3 and Figure 2). An emphasis is placed on scientific references to support the mechanisms and contributions of these constituents (Wang *et al.*, 2025).

### Polyphenols

Polyphenols represent the largest and most significant group of phytochemicals in apples. These compounds are predominantly located in the apple peel, though the flesh also contributes to overall polyphenol intake due to greater consumption volume. Apple polyphenols are classified into several groups, including flavonoids, phenolic acids, dihydrochalcones, and procyanidins. Their presence varies significantly based on variety, maturity, cultivation conditions, and storage practices (Liu *et al.*, 2021).

### Flavonoids

Flavonoids are a diverse group of polyphenols with substantial antioxidant, anti-inflammatory, and cardioprotective properties. Apples contain several subclasses of flavonoids, including flavonols, flavan-3-ols, anthocyanins, and dihydrochalcones, each contributing uniquely to the fruit's overall bioactivity (Oszmianski *et al.*, 2018).

### Flavonols

Flavonols, especially quercetin and its derivatives, are among the most abundant flavonoids in apples. Common quercetin glycosides found in apples include quercetin-3-galactoside, quercetin-3-rhamnoside, quercetin-3-glucoside, and quercetin-3-arabinoside. Apple peel can contain up to 20 times more quercetin than the flesh, making the peel a superior source of this potent antioxidant. Quercetin plays a significant role in free radical scavenging, modulation of cell signaling pathways, and inhibition of pro-inflammatory mediators. Its high antioxidant capacity contributes substantially to the overall health benefits associated with apple consumption (Wojdyło *et al.*, 2015).

### Flavan-3-ols

Flavan-3-ols such as catechin and epicatechin are present in both monomeric and polymeric forms. These compounds are highly effective in reducing oxidative stress, inhibiting platelet aggregation, and improving vascular function. Epicatechin, in particular, is recognized for its protective effects on the

endothelium and its potential role in reducing cardiovascular disease risk. Flavan-3-ols also serve as building blocks for procyanidins, which are more complex tannin molecules with significant antioxidant properties (Shoji *et al.*, 2024).

### Anthocyanins

Anthocyanins contribute to the red coloration of apple skins in varieties such as Red Delicious, Fuji, and Gala. The predominant anthocyanin is cyanidin-3-galactoside. Although present in smaller concentrations compared to other flavonoids, anthocyanins play crucial roles in reducing oxidative stress, enhancing immune function, and supporting cardiovascular health. Their presence is strongly influenced by light exposure, temperature fluctuations, and apple cultivar (Millán-Laleona *et al.*, 2023).

### Dihydrochalcones

Dihydrochalcones are unique to apples and are primarily located in the seeds and peel. The most notable dihydrochalcone is phloridzin (phloretin-2-glucoside), a compound of considerable interest due to its antidiabetic properties. Phloridzin acts by inhibiting SGLT1 and SGLT2, thereby reducing intestinal glucose absorption. This mechanism inspired the development of pharmaceutical SGLT2 inhibitors used in diabetes therapy. Phloretin, the aglycone of phloridzin, exhibits strong antioxidant and anti-inflammatory activities, contributing to cellular protection and reduced oxidative damage (Asale *et al.*, 2021).

### Phenolic Acid

Phenolic acids constitute another essential group of apple polyphenols and are categorized into hydroxycinnamic acids and hydroxybenzoic acids. These acids contribute to the flavor, aroma, and antioxidant potential of apples (Woźniak *et al.*, 2023).

### Hydroxycinnamic Acids

The predominant hydroxycinnamic acid in apples is chlorogenic acid (5-caffeoylquinic acid). This compound is known for its antioxidant, anti-inflammatory, and anti-obesity properties. Chlorogenic acid actively participates in modulating glucose metabolism and reducing postprandial blood glucose levels. It also influences enzymatic browning in apple flesh, a process mediated by polyphenol oxidase (Meland *et al.*, 2024).

### Hydroxybenzoic Acids

Hydroxybenzoic acids such as gallic acid, protocatechuic acid, vanillic acid, and syringic acid are present in smaller quantities. These compounds support antioxidant activity and possess antimicrobial and anti-inflammatory properties. Although not as abundant as other phenolics, their synergistic effects contribute to the overall bioactive profile of apples (Vander *et al.*, 2022).

### Procyanidins

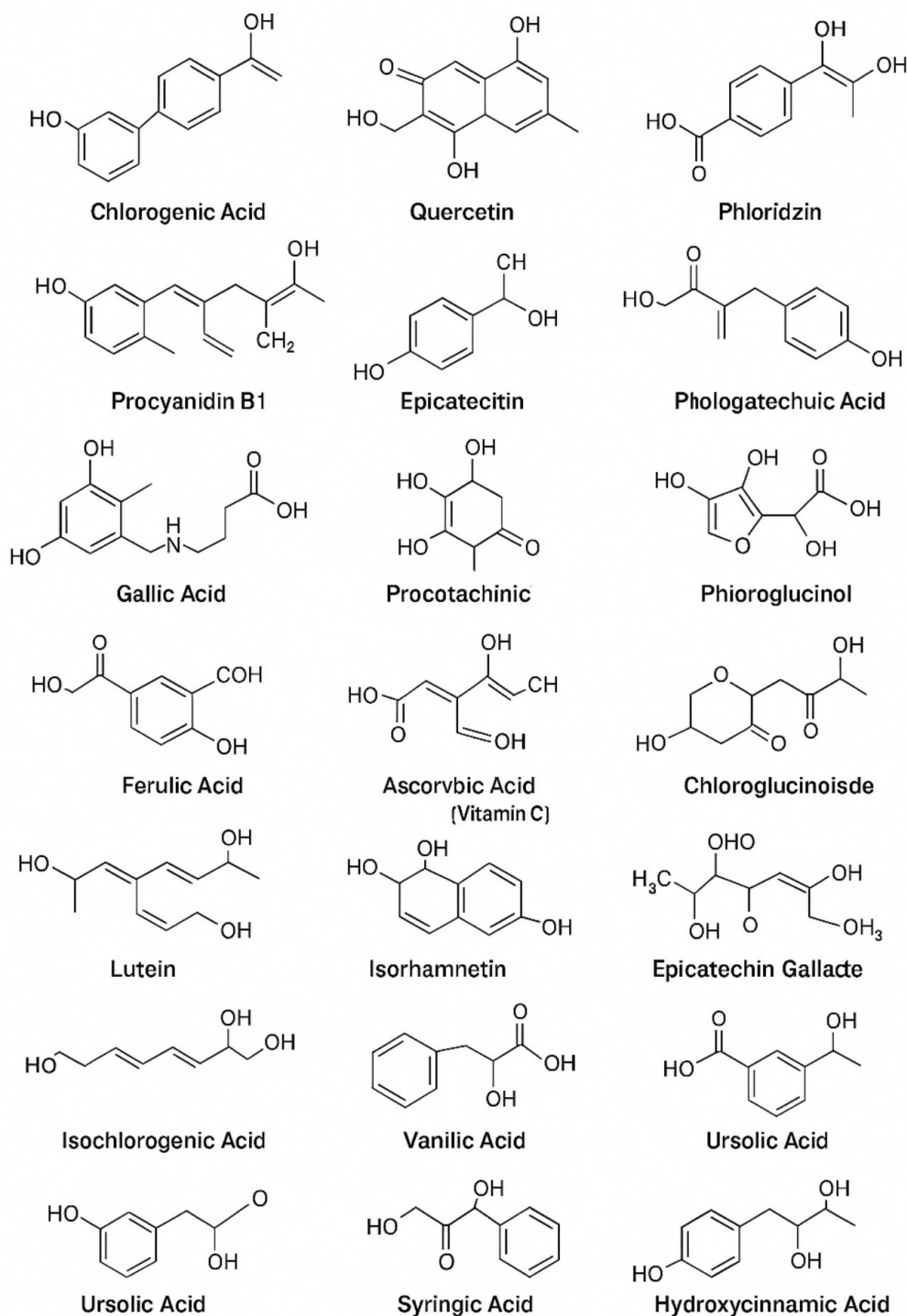
Procyanidins are polymeric flavan-3-ols composed primarily of epicatechin units. They are the most abundant phenolic compounds by mass in apples and are responsible for a significant portion of their total antioxidant capacity. Procyanidins have been shown to reduce oxidative stress, inhibit LDL oxidation, and improve endothelial function. They also exert beneficial effects on gut microbiota by serving as substrates for fermentation, which increases the production of beneficial short-chain fatty acids (Al Daccache *et al.*, 2020).

### Tannins

Tannins, including both hydrolyzable and condensed tannins, contribute to the astringency and bitterness of some apple varieties. Condensed tannins (proanthocyanidins) are far more common in apples than hydrolyzable tannins. These compounds possess antimicrobial, antioxidant, and anticarcinogenic properties. Their presence affects the sensory characteristics of apple cider and other apple-derived products (Koutsos *et al.*, 2015).



Figure 1: Apple plant.



**Figure 2:** Phytoconstituents of Apple.

### Triterpenoids

The waxy layer of apple peel contains a diverse array of pentacyclic triterpenoids, such as ursolic acid, oleanolic acid, and betulinic acid. These compounds are biologically active and have garnered significant scientific interest for their pharmacological properties (He *et al.*, 2008).

### Ursolic Acid

Ursolic acid is perhaps the most studied triterpenoid in apples. It is recognized for its anti-inflammatory, anticancer, antiviral, and muscle-enhancing properties. Research demonstrates that ursolic acid promotes muscle hypertrophy, reduces muscle wasting, and stimulates brown adipose tissue thermogenesis, which may aid in combating obesity. Its strong anti-inflammatory properties are mediated through suppression of NF- $\kappa$ B signaling, making

it a valuable compound for chronic disease prevention (Klocko, 2025).

### Oleanolic Acid and Betulinic Acid

Oleanolic acid has hepatoprotective, antimicrobial, and anti-inflammatory effects. It protects against oxidative liver damage and supports metabolic regulation. Betulinic acid exhibits anticancer properties by inducing apoptosis in cancer cells and inhibiting angiogenesis. Both compounds have promising potential for therapeutic applications (Moore *et al.*, 2011).

### Carotenoids

Carotenoids are naturally occurring pigments that contribute to the yellow, orange, and red hues of apples. Although present in lower concentrations compared to polyphenols, carotenoids play essential roles as antioxidants and precursors of vitamin A. Common carotenoids found in apples include  $\beta$ -carotene, Lutein, Zeaxanthin. These compounds are concentrated primarily in the peel. Lutein and zeaxanthin are known for their protective effects against age-related macular degeneration, while  $\beta$ -carotene plays a crucial role in immune function and skin health. The antioxidant actions of carotenoids complement the polyphenolic profile of apples and contribute to reducing the risk of chronic diseases (Ceci *et al.*, 2021).

### Vitamins and Micronutrients

Apples contain various vitamins and minerals that enhance and support the actions of phytochemicals. Vitamin C (ascorbic acid) is particularly abundant in apple peel and contributes to antioxidant defense by neutralizing free radicals. It also regenerates oxidized vitamin E and enhances the activity of polyphenols. Although apples are not the richest source of vitamin C compared to citrus fruits, the synergistic effect between vitamin C and apple polyphenols enhances overall antioxidant potential (Raczkowska *et al.*, 2024).

Vitamin E (tocopherols) though present in small quantities, protects cell membranes from oxidative damage. Apples also contain B vitamins, including thiamine (B1), riboflavin (B2), and pyridoxine (B6), which contribute to energy metabolism and nervous system function (Deusser H *et al.*, 2013).

### Minerals

Minerals such as potassium, magnesium, iron, and calcium are found in apples in moderate amounts. Potassium is particularly important for cardiovascular health, as it helps regulate blood pressure and maintains electrolyte balance (Minna *et al.*, 2019).

### Dietary Fiber and Pectin

Dietary fiber, specifically pectin, plays a vital role in the health benefits associated with apple consumption. Pectins are complex polysaccharides that form gels in the digestive tract, slowing

digestion and promoting satiety. This contributes to improved glycemic control, reduced cholesterol levels, and enhanced digestive health (Topp *et al.*, 2016).

Pectin has prebiotic properties, fostering the growth of beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus* species. These bacteria produce short-chain fatty acids that nourish colon cells, improve gut barrier function, and reduce inflammation. Additionally, the combination of pectin and polyphenols enhances antioxidant activity and supports metabolic regulation (Aprikian *et al.*, 2002).

### Volatile Compounds

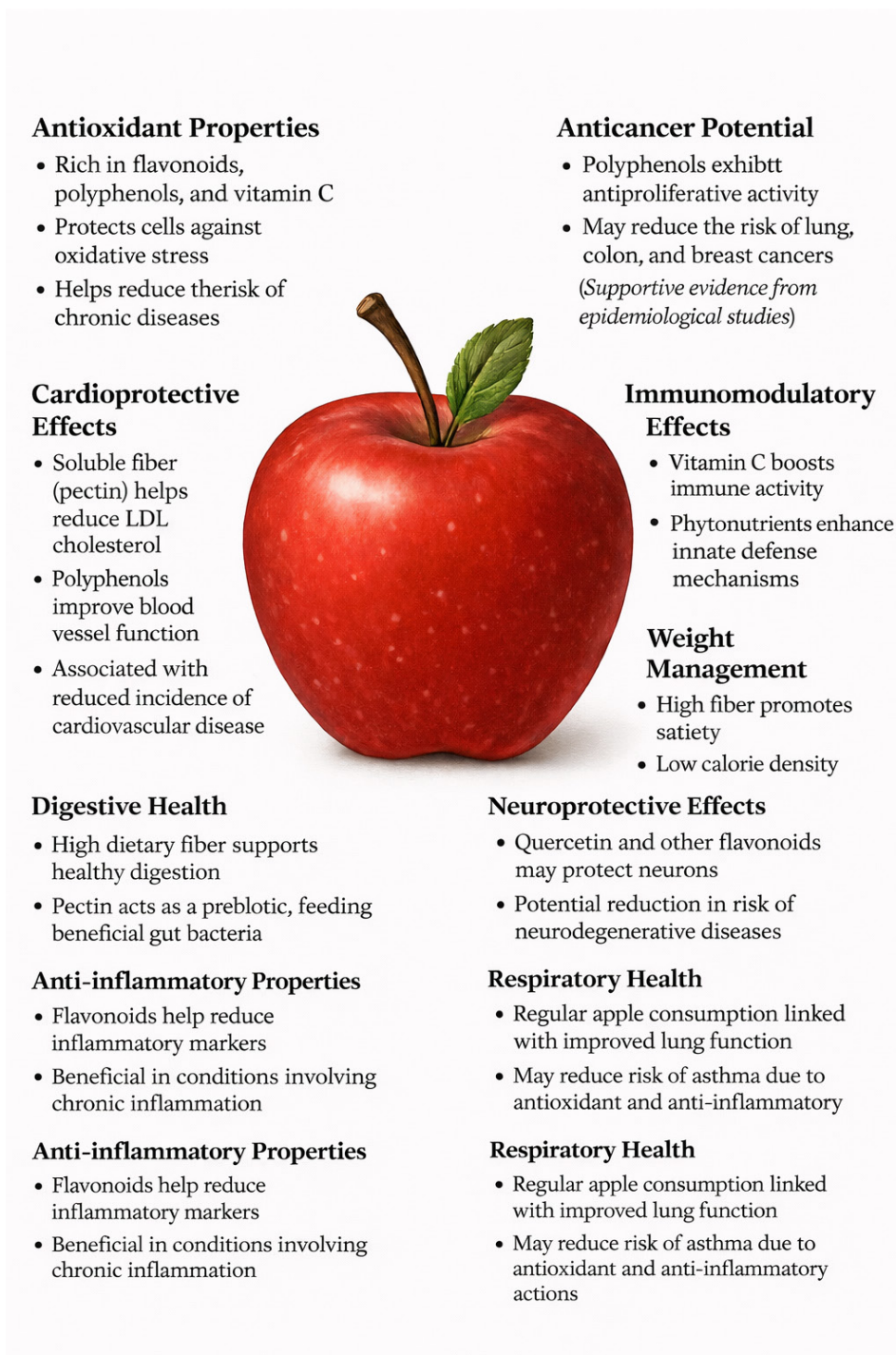
Apples contain over 300 volatile compounds responsible for their characteristic aroma and flavor. These volatiles include esters, aldehydes, ketones, terpenes, alcohols, and acids. The composition of volatile compounds varies by apple variety, ripeness, and storage conditions. Key volatiles include Hexyl acetate, Butyl acetate, Ethyl 2-methylbutyrate, Trans-2-hexenal,  $\alpha$ -farnesene,  $\alpha$ -Farnesene is abundant in apple peel and plays a crucial role in post-harvest storage behavior. It also possesses antimicrobial and antioxidant properties, contributing to the fruit's natural defense mechanisms (Leontowicz *et al.*, 2001).

### Pharmacological Activity

Historically, they have been used in traditional healing systems for digestion, immunity, and general health maintenance. Modern scientific research has validated many of these traditional uses, revealing complex biochemical mechanisms through which apples promote human health (Figure 3). Their therapeutic

**Table 1: Apple Varieties (Zielińska *et al.*, 2019).**

Variety	Description
Red Delicious	Deep red, mildly sweet, best for fresh eating.
Golden Delicious	Yellow, sweet, crisp, good for cooking and fresh eating.
Granny Smith	Green, tart, firm, excellent for baking.
Fuji	Very sweet, crisp, long shelf life.
Gala	Sweet, aromatic, reddish-orange stripes.
Honeycrisp	Very crisp, balanced sweet-tart flavor.
McIntosh	Soft, tangy, great for cider and applesauce.
Braeburn	Firm, spicy-sweet, good for fresh use and baking.
Jonagold	Sweet with slight tartness, hybrid of Jonathan and Golden Delicious.
Pink Lady (Cripps Pink)	Crisp, tangy, rosy color, long shelf life.
Cortland	Mildly tart, slow browning, ideal for salads.
Rome Beauty	Firm, holds shape when baked.



**Figure 3:** Therapeutic profile of Apple.

potential lies not simply in their vitamin content but in the synergistic actions of fiber, polyphenols, phytonutrients, and minerals (He *et al.*, 2008).

### Antioxidant Properties

One of the most widely studied therapeutic aspects of apples is their potent antioxidant activity. Apples contain polyphenols such as quercetin, catechin, epicatechin, chlorogenic acid, and anthocyanins. These compounds neutralize free radicals that

cause oxidative damage to cells. Oxidative stress is implicated in aging, cancer, cardiovascular diseases, and metabolic disorders. By reducing free radical load, apple consumption protects DNA, proteins, and lipids from damage, thereby maintaining cellular integrity and slowing degenerative processes (Maragò *et al.*, 2016).

**Table 2: Irrigation and cultivation of Apple (Pandey *et al.*, 2019).**

Aspect	Description
Climatic requirements	Temperate climate with 18-24°C temperature and adequate winter chilling.
Soil characteristics	Well-drained loamy soil rich in organic matter; pH 5.0-7.0.
Orchard establishment	Deep ploughing and leveling; pits enriched with farmyard manure.
Irrigation management	Regular irrigation, especially during flowering and fruit growth; drip preferred.
Nutrient management	Organic manure with balanced NPK; zinc and boron improve fruit quality.
Training and pruning	Central leader system with annual dormant-season pruning.
Pest and disease management	Codling moth, aphids; apple scab, powdery mildew, fire blight.
Harvesting	Manual harvesting at physiological maturity (August-October).
Post-harvest handling	Grading and proper storage to maintain quality and market value.

### Digestive Health Benefits

Apples are well known for supporting digestive health due to their high content of dietary fiber, particularly soluble fiber such as pectin. Pectin forms a gel-like substance in the intestines, improving stool consistency, preventing constipation, and supporting overall colon function. Fiber also acts as a prebiotic that feeds beneficial gut bacteria, fostering a healthier microbiome. Regular consumption of apples helps regulate bowel movements, improves nutrient absorption, and reduces the risk of gastrointestinal disorders such as diverticulitis and irritable bowel syndrome (Paturi *et al.*, 2014).

### Cardiovascular Health

The apples has been linked to better heart health due to fiber. By binding with bile acids in the colon increase their evacuation, lowers LDL cholesterol levels. They lowers the amount of cholesterol in the blood by forcing the liver to spend its cholesterol reserves to make more bile acids. Additionally, apple polyphenols stop LDL cholesterol from oxidizing, which is a crucial stage in the development of atherosclerosis. Additionally, by balancing the effects of sodium on vascular tension, potassium found in apples helps control blood pressure (Gogia *et al.*, 2015).

### Glycemic Control and Diabetes

Although apples contain natural sugars, they have a comparatively low glycemic index. Their high fiber content slows digestion, resulting in a gradual release of glucose into the bloodstream. Polyphenols in apples may also improve insulin sensitivity and influence carbohydrate metabolism. Research suggests that moderate apple consumption is associated with a reduced risk

**Table 3: Distribution of Phytochemicals in Apple Tissues (Paturi *et al.*, 2014).**

Apple Tissue	Phytochemical Distribution
Apple Peel	Richest source of polyphenols, triterpenoids, carotenoids, and vitamin C; contains up to six times more antioxidants than flesh.
Apple Flesh	Lower polyphenol concentration but important due to high consumption; contains phenolic acids and flavan-3-ols.
Apple Seeds	Contain phloridzin and amygdalin (a cyanogenic glycoside); small amounts safe but excessive intake should be avoided.

of type 2 diabetes, partly due to improved pancreatic beta-cell function and reduced inflammation in metabolic tissues (Guo *et al.*, 2019).

### Anti-inflammatory Effects

The chronic inflammation is one of the major cause for arthritis, cardiovascular disorders, diabetes, and even some cancers. Apples contain numerous anti-inflammatory compounds, including quercetin and other flavonoids, which can modulate inflammatory pathways. The antioxidants reduce the production of pro-inflammatory cytokines, resulting in decreased systemic inflammation. Regular consumption of apples may therefore contribute to improved joint health, lowered inflammation markers, and enhanced overall resilience to inflammatory conditions (López-Hortas *et al.*, 2018).

### Cancer Prevention Potential

Multiple studies suggest that apples may help reduce the risk of certain cancers, including colorectal, breast, and lung cancers. This effect is attributed to apples' rich antioxidant content, anti-inflammatory properties, and ability to enhance detoxification processes. Apple polyphenols inhibit cancer cell proliferation, induce apoptosis (programmed cell death), and prevent DNA mutations by neutralizing carcinogens. Fiber also contributes to cancer prevention by improving gut health and reducing exposure of intestinal cells to harmful substances (He *et al.*, 2007).

### Gut Microbiome Modulation

Immunity, mental health, metabolism, and digestion are all significantly impacted by the gut flora. Apples contain both soluble and insoluble fibers that feed beneficial bacteria such as *Bifidobacteria* and *Lactobacilli*. Apple polyphenols reach the colon largely undigested, where they are broken down by gut microbes into bioactive metabolites. This process improves microbial diversity, enhances gut barrier integrity, reduces inflammation, and promotes better digestive and metabolic health (Espley *et al.*, 2014).

## Immune System Support

Apples help strengthen the immune system primarily due to their vitamin C and antioxidant content. White blood cell formation, antibody responses, and epithelial integrity our first line of defense

against infections are all aided by vitamin C. Additionally, apple polyphenols reduce oxidative stress and inflammation, further enhancing immune resilience. Regular consumption of apples contributes to reduced frequency and severity of infections such as the common cold (Bai *et al.*, 2011).

**Table 4: Apple Phytoconstituents and Therapeutic Activities (Martin Valis, *et al.*, 2020).**

Sl. No.	Chemical Class	Phyto-constituent	Major Plant Part	Mechanisms of Action	Therapeutic Activities
1.	Flavonoids	Quercetin	Peel>Flesh	Scavenges free radicals; inhibits COX-2/LOX; modulates NF-κB and Nrf2.	Antioxidant, anti-inflammatory, cardioprotective, anticancer
2.	Flavanols	Catechin	Peel and Flesh	Enhances endothelial nitric oxide; inhibits LDL oxidation.	Cardioprotective, antioxidant, neuroprotective
3.	Flavanols	Epicatechin	Peel	Improves vascular function; reduces oxidative stress.	Cardioprotective, antioxidant
4.	Oligomeric Polyphenols	Procyanidins (B1, B2)	Peel>Seeds	Reduces lipid peroxidation; inhibits inflammatory mediators.	Antioxidant, vascular protection, anticancer
5.	Phenolic Acids	Chlorogenic acid	Flesh	Slows glucose absorption; suppresses lipid accumulation.	Anti-diabetic, hepatoprotective
6.	Dihydrochalcones	Phloridzin	Peel and Leaves	Inhibits SGLT1; antioxidant activity.	Anti-diabetic, anti-obesity
7.	Dihydrochalcones	Phloretin	Peel	Inhibits GLUT2; antimicrobial effects.	Anti-diabetic, antimicrobial
8.	Dietary Fibers	Pectin	Flesh and Peel	Lowers LDL; improves gut microbiota.	Hypocholesterolemic, prebiotic
9.	Triterpenoids	Ursolic acid	Peel	Induces apoptosis; suppresses cytokines.	Anticancer, anti-inflammatory
10.	Triterpenoids	Oleanolic acid	Peel	Hepatoprotective; anti-inflammatory.	Liver protection
11.	Vitamins	Vitamin C	Flesh	Enhances immune cell activity; collagen synthesis.	Immune boosting, antioxidant
12.	Vitamins	Vitamin E	Seeds and Peel	Protects cell membranes from oxidation.	Antioxidant, cytoprotective
13.	Minerals	Potassium	Flesh	Maintains electrolyte balance.	Blood pressure regulation
14.	Organic Acids	Malic Acid	Flesh	Enhances energy metabolism.	Skin health, fatigue reduction
15.	Pigments	Carotenoids	Peel	Free radical scavenging; vitamin A precursor.	Vision support, antioxidant
16.	Pigmented Flavonoids	Anthocyanins	Red Peel	Upregulates antioxidant enzymes.	Cardioprotective, anti-aging
17.	Polyphenols	Tannins	Peel and Seeds	Protein precipitation; antimicrobial.	GI protection, antioxidant

## Weight Management Benefits

High fiber and water content make apples as a popular choice of fruit. Eating apples before meals has been shown to reduce overall calorie intake. The slow digesting of carbohydrates help to stabilize blood sugar levels, reducing cravings and preventing overeating. Moreover, apples low energy density allows for larger volume consumption without excessive calorie load, making them ideal for weight-control diets (El-Messery *et al.*, 2018).

## Liver and Detoxification Support

The liver is responsible for detoxifying chemicals and metabolizing nutrients. Apples support liver health through their antioxidants, which protect liver cells from oxidative damage. The fiber in apples helps remove toxins and heavy metals by binding to them in the digestive tract, reducing the liver's workload. Certain apple compounds may also support phase II detoxification enzymes, which play a role in processing and eliminating harmful substances (D'Argenio *et al.*, 2012).

## Neurological Health

Apples contain neuroprotective properties. Quercetin and other polyphenols shield neurons from oxidative stress, which is a major contributing cause to neurodegenerative illnesses including Parkinson's and Alzheimer's. Some research indicates that apple consumption enhances acetylcholine levels, improving memory and cognitive function. Additionally, the anti-inflammatory actions of apples contribute to better brain aging and reduced risk of neurological decline (Spengler *et al.*, 2019).

## Skin Health

Apples contribute to healthy skin through their rich antioxidant and vitamin content. Collagen synthesis, which keeps skin tight and elastic, depends on vitamin C. Apple extracts have been used in traditional skincare remedies to reduce acne, brighten complexion, and hydrate the skin. The antioxidants in apples help protect skin cells from UV damage and environmental pollutants that accelerate aging (Boyer *et al.*, 2004).

## Bone Health

Polyphenols in apples reduce oxidative stress and inflammation and played significant roles to maintain bone density and bone loss. Some studies suggest that apple consumption may increase bone mineral density by supporting osteoblast (bone-forming cell) activity. Their potassium content also helps balance acid levels in the body, reducing calcium loss from bones (Can *et al.*, 2014).

## Respiratory Health

Several studies have linked apple consumption to better respiratory outcomes. The antioxidants and flavonoids in apples help reduce airway inflammation, making them beneficial for

individuals with asthma. It also improved lung function and reduced risk of COPD. Their anti-inflammatory and antioxidant actions protect lung tissues from damage caused by pollution and allergens (Lee *et al.*, 2003).

Apples are a highly nutritious fruit offering a wide range of therapeutic benefits. Their rich composition of fiber, polyphenols, vitamins, minerals, and antioxidants contributes to improved digestion, cardiovascular health, metabolic regulation, immune support, and protection against chronic diseases. Incorporating apples into daily diets is a simple yet powerful strategy for promoting long-term health and disease prevention (Table 4).

## Future directions

Apple cultivation in India has promising prospects if existing challenges are effectively managed. At present, growers struggle with changing climate patterns, reduced chilling hours, rising pest and disease incidence, poor soil fertility, and increasing input expenses, all of which lower productivity and fruit quality. The future of apple farming depends on adopting climate-resilient and low-chill varieties along with high-density planting systems to improve yields and returns. Greater focus on balanced nutrition and eco-friendly pest control can help minimize losses. Expanding processing options like juices, dried products, and functional foods can add value. With research-based cultivation practices and better post-harvest management, apple production can remain sustainable and economically rewarding.

## CONCLUSION

Apples are a nutritionally dense and therapeutically significant fruit enriched with diverse phytochemicals such as polyphenols, flavonoids, triterpenoids, vitamins, and dietary fiber. Their antioxidant, anti-inflammatory, cardioprotective, antidiabetic, and anticancer activities make them an important component of preventive nutrition. India, especially Kashmir, plays a major role in apple cultivation, supporting both the economy and rural livelihoods. Scientific evidence strongly supports the traditional belief that apples contribute to overall health and chronic disease prevention. Continued research, improved cultivation practices, and enhanced post-harvest management can further unlock the fruit's nutritional, medicinal, and economic potential.

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## ABBREVIATIONS

**WHO:** World Health Organization; **pH:** Potential of Hydrogen; **°C:** Degree Celsius; **FAO:** Food and Agriculture Organization; **g:** Gram; **kg:** Kilogram; **SGLT:** Sodium Glucose Transporters;

**SGLT1:** Sodium/Glucose Cotransporter 1; **SGLT2:** Sodium/Glucose Cotransporter 2; **LDL:** Low-Density Lipoprotein; **NF- $\kappa$ B:** Nuclear Factor kappa-light-chain-enhancer of activated B cells; **DNA:** Deoxyribonucleic Acid; **UV:** Ultraviolet; **COPD:** Chronic Obstructive Pulmonary Disease; **COX:** Cyclooxygenase; **LOX:** Lipoxygenase; **Nrf2:** Nuclear Factor Erythroid 2-Related Factor 2; **ROS:** Reactive Oxygen Species; **GLUT2:** Glucose Transporter 2; **DPI:** Dots Per Inch.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

## AUTHOR CONTRIBUTIONS

Vakkalagadda Ravi Kumar contributed to the conceptualization and initial drafting of the manuscript. Reena Singh and Tandrima Majumder were involved in data collection and organization of the literature. Ameenuzzafar Zafar prepared all figures and tables. Sayyad Mustak and Shaik Harun Rasheed performed critical proofreading and ensured consistency and coherence throughout the manuscript. Sandip Sen supervised the study and finalized the manuscript for submission.

## SUMMARY

Apple (*Malus domestica*), a fruit belonging to the Rosaceae family, holds great importance worldwide due to its nutritional, economic, and health-promoting value. In India, apple cultivation is largely confined to the Himalayan states of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, where suitable climatic and soil conditions support quality production and provide livelihoods to thousands of farmers. Apples are rich in health-enhancing compounds such as flavonoids, phenolic acids, and triterpenoids etc. Scientific research supports the traditional belief that regular apple consumption helps reduce the risk of chronic diseases such as heart ailments, diabetes, cancer, and neurological disorders. However, apple farming in India faces challenges from climate change, declining soil fertility, pests, and rising costs. Adopting climate-resilient varieties, modern planting systems, eco-friendly management practices, and value-added processing can ensure sustainable and profitable apple production.

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