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Integrative Perspectives on *Ficus carica* (Moraceae): Mechanistic Insights, Phytochemical Diversity, Genetic Basis, and Formulation Potential

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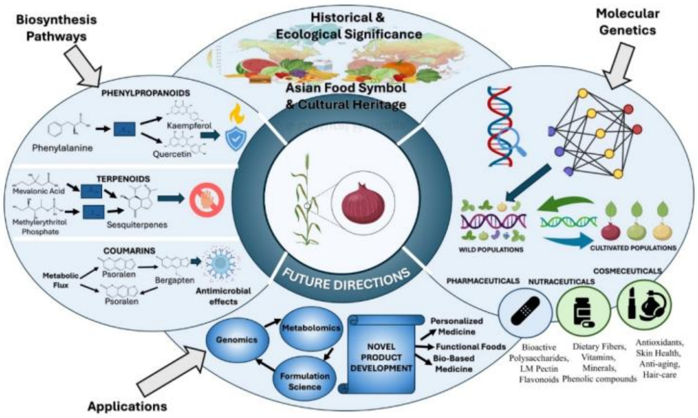
ABSTRACT
Ficus carica is one of the earliest food in history and its nutritional value, medicinal importance and ecological niche are no less significant as well especially in temperate regions of several mediterranean, middle eastern and asian countries. This review gathers some available data on its taxonomic, botanical and physiological features bringing attention to complex biosynthesis pathways of secondary metabolites (phenylpropanoids, terpenoids, coumarins) which are responsible for antioxidant activities as well as anti-inflammatory responses and stress resistance in this semi aquatic plant. Molecular genetics findings demonstrate complex networks of genes underlying these pathways, extensive genetic variation among and within wild and cultivated populations that contribute many of the adaptive traits generated, including variation in phytochemical diversity. Its special natural occurrence properties from LM pectin to bioactive polysaccharides can be exploited in different pharmaceutical, nutraceutical and cosmeceutical uses. Despite rich traditions and new molecular data, we observed a shortage of integrative studies that engage with metabolomics, genomics and formulation science. This review emphasizes these knowledge deficits and potential future avenues for mechanistic understanding and novel product development to exploit the whole therapeutic properties of *Ficus carica*.
Keywords: *Ficus carica*, Phytochemical diversity, Secondary metabolites, Genetic regulation, Formulation potential.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The fig also known as *Ficus carica* is one of the oldest cultivated trees yielding fruit and is a very important part of nutrition and medicine in many cultures, which makes it vital in traditional medicines and diets across mediterranean, Middle eastern, and Asian regions. It belongs to the family Moraceae and is part of one of the largest genera of angiosperms, which comprises 750-800 species of trees, shrubs, climbers, and epiphytes that are native to tropical and subtropical regions. Botanically, it is a small, deciduous tree or shrub characterized by lobed leaves and a characteristic syconium, an enclosed inflorescence that forms the edible fig fruit, rich in sugars, minerals, polyphenols, and bioactive compounds. History: The fig tree is native to the Mediterranean region and Western Asia, but their culture has spread throughout the world over thousands of years. Apart from nutritional importance *F. carica* has also been a component of traditional medicinal systems, including Unani, Ayurvedic, and Middle Eastern medicine, and its ecological and genetic value to the vast class of Ficus species [1,2].

Its fruits, leaves, roots, bark and latex are used traditionally to cure indigestion, diarrhoea, colic pain or griping, sore throat or mouth; cough; bronchitis; cardiovascular diseases; inflammatory diseases such as boils and even gonorrhea and leprosy etc.; ulcers of skin and blood. It is also known for properties like laxative, tonic, diuretic, astringent, antipyretic and aphrodisiac. The latex is used as an anthelmintic due to the presence of active enzymes and the fruits are part of food regimens for nutritional and restorative intentions. These wide in-scope applications underline the serious ethnomedicinal value of F. carica in traditional medicinal systems [3].

Nutritional value *Ficus carica* has some nutritional value, it provides the following essential minerals potassium, calcium, magnesium and iron as well as dietary fiber and natural sugars. It is also a decent source of vitamins and while it offers vitamin C, B-complex vitamins (particularly thiamine and pantothenic acid), vitamin K, as well as less low amounts of vitamin A and vitamin E. which ensure energy production, optimal gastrointestinal tract function, mineral balance within the body and antioxidant protection from harmful free radicals [4]. Leaves of *Ficus carica* are highly medicinally valued and possess proved antidiabetic, antioxidant, anti-inflammatory, anticancer, antimicrobial, hepatoprotective as well as renoprotective activities. They are commonly, historically, and pharmacologically used in the treatment of diabetes, hemorrhoids, herpes zoster etc due to their various polyphenolic content. [5]. The latex from *Ficus carica* and its bioactive enzymes have an industrial potential in pharmaceutical, food, cosmetic and biotechnology industries for exploring natural preservative agents, therapeutic products and cosmetic bioactive formulations [6].

The literature on *Ficus carica* (Moraceae) shows that there are three main knowledge gaps. The first is due to the absence of in depth mechanistic analysis to elucidate how its numerous bioactive molecules act. The majority of the studies do not combine all these compounds to determine their synergistic bioactivity and concentrate on individual phytochemicals groups, such as phenolics or flavonoid. Second, little work is devoted towards the F. carica formulation properties and how its chemical diversity impacts on the stability, delivery and efficiency in medicine or supplement products. Studying of these molecular phenomena, chemical interactions and formulation methods could lead to an optimal exploitation of the therapeutic potentials for *Ficus carica* in actual medicine and industry.

2. TAXONOMY, BOTANY, AND MORPHO-PHYSIOLOGY

2.1 Taxonomic placement within Moraceae: This plant is ecologically important, many animals feed off it and live in it. It also interacts with necessary symbionts like arbuscular mycorrhizal fungi to improve nutrient accessibility and stress tolerance. There are also other adaptations in *Ficus carica* which create possibilities for survival in arid and nutrient poor ecosystems, which contribute to the stability of ecosystem and biodiversity preservation[7]. The Taxonomic and botanical features of *Ficus carica* are summarized in the following table, which highlights its classification, morphological traits, and key reproductive characteristics.

Table 1: Taxonomy and Botanical Features of *Ficus carica*

Characteristic	Description
Family	Moraceae
Genus	Ficus
Species	carica L.
Subgenus and section	Ficus (subgenus), Caricae (section)
Growth Habit	Deciduous small tree or large shrub, spreading crown
Leaf Morphology	Large, lobed leaves with aromatic components
Reproductive Structure	Syconium (fig fruit) enclosing multiple small flowers
Roots	Well-developed, adapted to diverse soil conditions
Pollination Biology	Obligate mutualism with species specific fig wasps
Physiological Traits	Stress response adaptions including drought tolerance and metabolite accumulation
Distribution	Native to Mediterranean and western Asia, cultivated globally


Figure 1: Leaves of *Ficus carica*


Figure 2: Stem of *Ficus carica*


Figure 3: Fruit of *Ficus carica*


Figure 4: Bark of *Ficus carica*

2.2 Growth habit, morphology, and anatomy

Fruit (syconium), leaves, roots, reproductive biology

The fig bud will take 12 weeks to become a mature syconium, with another 5 for ripening. Growth is double-sigmoid shaped, with rapid early size. The syconium is green becoming red at ripening. *Ficus carica* is gynodioecious, (female and male trees exist) but the genes determining sex have not been discovered; female plants are used for seed production in the subgenus figs, but both female and male plants are found among subgenera Urostigma [8]. Its reproductive cycle is tied to a mutualism with fig wasps. Fruit development is hormone regulated (ethylene, ABA) in which pollinated and parthenocarpic fruits display differentiation in gene expression and hormonal profiles and the over-all picture speaks of a multifaceted reproductive biology[9].

This is a deciduous plant with lobed leaves and fruits such as fig. Cultivars differ greatly in leaf size, shape and number of lobes and are reliable identification characters. The leaves are usually five-lobed and three-lobed or seven-lobed leaves also occur. Differences in the length and width of laminae, petiole, depth of sinuses and angle between lobes can be used to distinguish cultivars, furthermore contemporary morphometric characterizations involving image-based techniques that support machine-learning options offer faster decision-making outcomes in an objective manner using leaf classification [10].

The root system of *Ficus carica* is primarily a fibrous and adventitious one, especially in cuttings. Root length, surface area and ratio of fine roots to coarse roots are all affected by cutting type and growth medium, with longer cuttings and growing media such as perlite or cocopeat increasing the success rate of rooting [11,12]. Two types of roots are present under in vitro conditions, fine aerial and larger substrate embedded [13].

Ficus carica demonstrates a gynodioecious system, having both separate male (caprifig) and female (edible fig) trees, and must rely on an obligate mutualism with the fig wasp Blastophaga psenes for reproduction [14]. The syconium operates as a closed inflorescence in which male and female flowers coexist and are pollinated and produce seeds through the exchange of pollen by wasps. Specialized floral types and stages of development ensure proper timing of wasp entrance, oviposition, and pollen release [15]. Developmental pathways leading to fruit formation can occur either by way of pollination or parthenocarpy, responding to different hormonal signals and gene expression profiles [16].

2.3 Physiological traits

It is moderately drought and salt stress tolerant. It protects itself by shedding leaves, thereby preserving water, slowing down photosynthesis, or by the closure of leaf pores. The plant manufactures various protective chemicals such as proline and antioxidants. Different varieties of fig plants have different degrees of tolerance to stresses [17]. Special genes FcJA2 specifically enable survival under harsh conditions. Fig trees require special wasps for the pollination, which is essential to their reproductive cycle [18].

Ficus–pollinator mutualism

Ficus carica has a unique mutualism with fig wasps, Blastophaga psenes, which is highly important for its reproduction. The syconium is an unusual, hollow form of the fruit. Females can invade it only through a small opening while transporting pollen from other figs [19]. Some lay eggs inside certain flowers while others leave behind seeds, so both wasps and figs get something out of the deal. Its framework, fragrance and timing of bloom have all been perfectly calibrated to attract its wasp species that will guarantee a successful pollination and reproducing. Very small differences in the scent of the fig can break this close liaison, citing their co-evolution and species-specificity. [20].

Stress physiology

Different physiological and biochemical strategies are adopted by *Ficus carica* to reveal its strong adaptation to drought and harsh environments. *Ficus carica* uses diverse physiological and biochemical strategies to demonstrate its powerful adaptation to drought-stress conditions [21]. Deep and widespread root system can fetch water from dry soil, complemented by thick lobed leaves bearing well distributed stomata minimizes the water loss. In response to stress, the tree prorogates Osmo protectants such as proline and antioxidants like phenolics and flavonoids that act on manage cells damage from all reactive oxygen species [22]. Figs maintained photosynthesis efficiently by recovering the light stress damage and adapting their stomatal conductance for optimal CO2 uptake. Root-to-shoot ratios and root biomass also adjust to enhance resistance to water or nutrient deficiency. These adaptive characters collectively enable *F. carica* to survive and grow in water limited arid, semi-arid mould mediterranean conditions that prevail in the natural habitats of this crop [11].

Metabolite accumulation patterns

The metabolites profile of *Ficus carica* revealed its adaptations and therapeutic potential. Primary metabolites like sugars (fructose, glucose) and organic acids (malic, citric) accumulate during fruit ripening for taste improvement and seed disperser attraction [23]. Oxy- prenylated secondary metabolites among other bioactive compounds in sweet basil are phenolics and flavonoids, which play a role in defence against stress factors, herbivores, and microorganisms; their content depends on the environment and cultivar [24]. Leaves and latex include psoralen and bergapten (defence molecules with also medicinal properties). The volatile furfurals, terpenes involved in pollinator attraction are developmentally regulated. Under stress, compounds like caffeic acid derivatives increase, enhancing antioxidant defences and tissue resilience[25].

Morphological characteristics of Ficus species vary greatly within and among different species. These differences are determined both by genetic predisposition and environmental influences. Following table shows the characteristics to be considered when comparing the different species include leaf shape and size, margin type, apex, base and internal structures.

Table 2: Comparison of morphological characteristics among Ficus species

Species/Group	Leaf Shape & Size	Leaf Margin	Leaf Base	Notable Anatomical/ Other Features	References
F. carica	Lanceolate, 7-9 cm long, 4-6 cm wide; palmately 3-5 lobed	Serrate	Cordate	Bifacial mesophyll, crystals in epidermis	[26]
F. elastica	Elliptic, large	Entire	Obtuse	Glabrous, isobilateral mesophyll	[27]
F. religiosa	Ovate, variable	Entire	Cordate	Cystoliths on abaxial layer	[27]
F. benjamina	Elliptic, acute to round base	Entire	Acute/ round	Spiral arrangement, anatomiacal cluster	[27]
F. microcarpa	Small, elliptic	Entire	Cuneate	Smallest leaf length/ width	[27]
F. hispida	Large, serrate- dentate margin	Serrate-dentate	Cordate	Largest leaf area, unique, lobation	[28]
F. glumosa	Variable, significant variation	Serrate/ entire	Cordate/obtuse	Significant seasonal variation	[28]
Hemiepiphytic Ficus (H)	Small, thick, high LMA (Leaf Mass per Area)	Entire	Variable	High wood/ root density, drought tolerant	[28]
Non- hemipiphytics Ficus (NH)	Large, thin, high stomatal density	Entire/serrate	Variable	Greater specific root length, fast growth	[29]

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3. MECHANISTIC BASIS OF SECONDARY METABOLITE PRODUCTION

3.1 Biosynthetic pathways

Phenylpropanoid pathway: In *Ficus carica*, the phenylpropanoid pathway starts with shikimate-derived amino acid phenylalanine, which is transformed by CAL to cinnamic acid; PAL is tightly controlled epigenetically by developmental and environmental factors such as drought or UV [30]. Hydroxylation of the cinnamic acid by cinnamate 4-hydroxylase (C4H) results in the production of p-coumaric acid, which, upon CoA ligation by 4-coumarate CoA ligase (4CL), generates the precursors for important branches like flavonoids, lignin and phenolic acids [31]. Flavonoids flavonols anthocyanins responsible for pigmentation, UV protection, and lignin biosynthesis monolignols are used to synthesize structural polymers that reinforce cell walls and mediate stress resistance, 48 phenolic acids (as caffeic acid, gallic acid) antioxidant defenses. In *Ficus carica*, these metabolic pathways are activated under biotic and abiotic stress in response to defence and adaptative processes with transcriptional regulation of the PAL, C4H, and 4CL genes coupled to metabolite content [32]. The biosynthesis of psoralen, a phenylpropanoid-derived furanocoumarin, in *Ficus carica*, is unique principally because of its role as an antioxidant and UV protectant that modulates drought stress. These compounds have also been regarded for their high medicinal and economic value, showing the importance of the pathway in plant physiology and adaptation [33].
Terpenoid & sterol pathways: The terpenoid pathway for *Ficus carica* is composed of two major pathways, the mevalonic acid (MVA) pathway located in cytoplasm and the methylerythritol phosphate (MEP) pathway located in plastids, which all resulted in universal precursors IPP and DMAPP [34]. These precursors undergo polymerization by prenyltransferases producing intermediates, GPP, FPP, and GGPP as substrates of terpene synthases (TPSs) that are responsible for the biosynthesis of a wide array of terpenes such as monoterpenes, sesquiterpenes, diterpenes and triterpenes [35]. In *Ficus carica*, limonene and pinene are known to be important in pathogen defense and pollinator attraction. Triterpenoids, that is, lupeol and ursolic acid are the active compounds which have an antioxidant and anti-inflammatory nature. The branched FPP biosynthetic pathway leads to squalene, cyclization of which produces cycloartenol and downstream phytosterols including stigmasterol and β-sitosterol. Sterols are indispensable for the stabilization of membrane, signaling, and response to stresses; they also serve as brassinosteroid precursor plant hormones that regulate growth and stress responses [36]. Control of pathways for biosynthesis of sterols and terpenoids is tight at both enzyme and transcriptional levels in response to developmental cues and other environmental stresses, whereas crosstalk controls directionality of the metabolic flow toward equal production of cellular membrane components versus secondary metabolites [37]. Regarding *Ficus carica*, the therapeutic potential and resistance to environmental stress might be improved by increasing the production of terpenoids (and sterols) through advancement in genetics/enhancement techniques including use of methyl jasmonate [38].
Coumarin and furanocoumarin synthesis: Coumarins and furanocoumarins in *Ficus carica L.* Secondary metabolite biosynthesis in the integration between light response and plant defense: second level of oxidative stress. Coumarins are derived from p-coumaroyl-CoA and ortho-hydroxylation of hydroxycinnamic acids gives rise to 7-OH coumarin ring system umbelliferone, mediated by cytochrome P450s such as CYP71B129 [39,40]. The furanocoumarin biosynthetic pathway shows that the first step from the common precursor umbelliferone, catalyzed by umbelliferone dimethylallyl transferase FcPT1 of *Ficus carica* demethylsuberosin, involves prenylation [41]. This is subsequently transformed by CYP76F112 (marmesin synthase) to marmesin, a precursor of psoralen, the fundamental linear furanocoumarin [42]. Additional diversity in furanocoumarins is provided by enzymes such as CYP71B130/131a, which can synthesize both linear (i.e., psoralen) and angular (i.e., angelicin) types [43]. These pathways utilize specific enzymes and are strictly controlled, resulting in the defensive and medicinal properties of the plant.

3.2 Cellular and molecular regulation: The cellular and molecular control of phytochemical synthesis in *Ficus carica* is associated with their regulation influence of phytochemical biosynthesis through multigenic, multitailored mechanism. Major families of key enzymes such as cytochrome P450s (CYP71B), glutathione S-transferases, CHS and DFR are involved in the biosynthesis, modification and transport of metabolites including flavonoids, coumarins, furanocoumarins [40]. Biosynthetic genes are also transcriptionally regulated by MYB, bZIP, MADS-box, WRKY and bHLH family transcription factors in response to environmental and developmental signals to maximize metabolic flux through these pathways [44,45]. GSTs are particularly involved in the vacuolar sequestration and sequestration of phytochemicals such as anthocyanins, which further provide compartmentalisation and cellular protection against toxicity [46]. This metabolic tuning mechanism allows *Ficus carica* to fine-tune the biosynthesis of secondary metabolite in a dynamic way, likely involved in defense responses, stress tolerance and development.

3.3 Environmental influences: *Ficus carica* is also able to adjust its growth in different environments by modifying its physiology and secondary metabolites contents. High temperatures increase the number of phenolic compounds in leaves, whereas low temperature can decrease valuable metabolites for storage [47]. Drought stress induces leaf abscission associated with decline in photosynthesis but enhances protective metabolites like α-tocopherol and Osmo protectants such as proline and sugars to adjust cell balance; transcription factors, including NAC helps improving the level of tolerance to drought [48,49]. The fig withstands moderate salinity levels through maintenance of constant leaf water and chlorophyll content, sugar metabolism, and stress genes induction [50,51]. Elevation plays an important role in fig physiology through its influence over temperature and water availability, at higher elevations stress responses will be favoured by drier conditions [49]. Metabolites and enzymes fluctuate during fruit development with a maximum at ripening along with an elevated flavonoid gene activity [52]. This environmental responsiveness of grow with and seedling phytochemical diversity is underpinned by this new form of environmental genetic regulation which enables Ficus carica to both maintain growth as well as maintain phytochemical-richness in the face of different climate conditions and stressors [53].

4. PHYTOCHEMICAL DIVERSITY OF *FICUS CARICA*

Ficus carica, abundant with various phytochemicals that are found in its fruits, leaves, stem bark and roots. These compounds are responsible for its nutritive, medicinal and functional food applications.

Table 3: Major Phytochemicals Identified in Different Parts of *Ficus carica*.

Plant Part	Main Phytochemicals Identified	Notable Compounds & Details	References
Fruits	Flavonoids, phenolic acids, anthocyanins, coumarins, terpenoids, alkaloids, organic acids, sugars, vitamins	Flavonoids glycosides, prenylated flavonoids, pelargonidin/cyanidin anthocyanins, chlorogenic acid, rutin, vitamin C, B vitamins, minerals	[54–56]
Leaves	Flavonoids, coumarins (furanocoumarins), polyphenols, terpenoids, saponins, organic acids	Rutin, quercetin derivatives, psoralen, bergapten, caffeic/ferulic, malic acids, sesquiterpenes	[57]
Bark/Roots	Polyphenols, triterpenoids, saponins, coumarins, flavonoids	Chlorogenic acid, rutin, psoralen, bergapten, caffeic/ ferulic/malic acids, sesquiterpenes	[58]
Volatiles	Aroma compounds, essential oils, monoterpenes, sesquiterpenes, aldehydes, alcohols, esters	Linalol, eugenol, β- caryophyllene, vanillin, benzyl alcohol, heptanal, nonanal	[59]
Polysaccharides	Glucose, galactose, rhamnose-based polysaccharides	Bioactive polysaccharides with immunomodulatory and antioxidant effects	[60]

5. INTRINSIC FORMULATION PROPERTIES OF *FICUS CARICA*

Ficus carica, exhibits particular interesting internal formulation characteristics far beyond latex including fruit pulp, pectin, mucilage and whole plant extracts that demonstrate properties of formulation. These properties are especially important in the production of pharmaceutical, nutraceutical and cosmeceutical formulations.

5.1 Physicochemical characteristics relevant to formulation: *Ficus carica* contains low-methoxyl pectin, having excellent pseudoplastic and thixotropic characteristics; its viscosity increases as concentration grows and decreases with the raise in temperature [61]. This renders it a very interesting candidate to be used as gelling agent, hydrogel former and stabiliser in both food and pharmaceutical dispersions. The native sugars in the fruit have stabilizing and osmoactive effects that provide moisture retention and texture to any formulation [6]. The extraction processes such as deep eutectic solvent assisted extraction contribute to improve the pectin yields and qualities, along with that providing fissible industrial applications without depleting universe of the raw material [62].

5.2 Antioxidant-based preservation: *Ficus carica* extracts especially from the peel and latex are highly phenolic rich source, flavonoids and anthocyanins with strong antioxidant activity [63]. These antioxidants again, have an application to extend the shelf life of foods and tropical prevents oxidative spoilage therefore fig extracts are valuable as natural preservatives [64].

5.3 Emulsifying and gelling potential: Fruit pulp and pectin of *Ficus carica* exhibited satisfactory gelling as well as emulsifying property, which could be employed for hydrogels, creams, or tropical delivery. The molecular structure if this pectin allows the formation of stable emulsions and gelation, which is a prime requisite for controlled drug release and cosmetic applications [65].

5.4 Compatibility with drug delivery systems: These bioactive polysaccharides and mucilage extracted from *F. carica* are suitable with novel drug delivery based systems such as nanoparticles, emulsions, tablets and nutraceutical syrups. Such compositions add stability, bioavailability and a controlled release of the active material [66].

5.5 Cosmeceutical relevance: Cosmeceutical applications extract of Figs have been shown to provide anti-aging, skin-lightening, and moisturizing effects on the skin by means of their enzyme inhibitory activities (eg tyrosinase inhibition) as well as its high antioxidant activity. These attributes make *Ficus carica* a potential addendum for cosmeceutical preparations used in cosmeceuticals for skin care and revitalization [67].

Table 4: Functional properties important for formulation development

Property/Component	Source/Extraction	Key Functional Role in Formulation	Example Applications	References
Low-methoxyl pectin	Fruit pulp, peel	Gelling, Thickening, Stabilizing	Hydrogels, jellies, drug carriers	[68]
Natural sugars	Fruit pulp	Osmotic activity, Moisture retention	Syrups, stabilizers, humectants	[69]
Mucilage	Whole fruit, peel	Emulsifying, Film-forming, Viscosity	Edible coatings, nanocarriers	[69]
Phenolic antioxidants	Peel, latex, whole fruit	Antioxidant, Preservative, Anti-aging	Shelf-life extension, cosmeceuticals	[70]
Flavonoids/Anthocyanins	Peel, fruit	Radicle scavenging, Color, Skin benefits	Skin-brightening, anti-aging	[71]
Polysaccharides	Fruit, peel	Immunomodulation, bioactivity	Functional foods, nutraceuticals	[72]
Enzyme inhibitors	Peel extracts	Tyrosinase, α-glucosidase inhibition	Skin-lightening, anti-diabetic	[73]
Emulsifying capacity	Pectin, mucilage	Emulsion stabilization, Gel formation	Creams, lotions, food emulsions	[74]
Nanoparticle compatibility	Mucilage, pectin	Drug delivery, Controlled release	Nanocarriers, tablets, syrups	[75]
Moisturizing agents	Fruit pulp, mucilage	Hydration, Skin barrier support	Moisturizers, topical gels	[67]

6. GENETIC IMPORTANCE FOR TRAITS AND PHYTOCHEMISTRY FOR *Ficus carica*

Ficus carica is a high economic and nutritional value crop with distinctive fruit development, and abundant phytochemical content. Recent progress in genomics has shed light on the genetic control of its major traits, diversity and adaptation and offers new opportunities for breeding and conservation.

6.1 Genome Organization: Description of the Chromosomes and Important Genes: Dense assemblies at the chromosome level have located the *F. carica* genome to 13 chromosomes, and enabled the investigation of important evolutionary events such as whole-genome duplication and chromosomal rearrangements that led to its domestication and trait diversity [76]. The key genes are MADS-box (FcAGL6, FcAP2 and FcSEP1/2) for fruit development, FcANS and FcCHS10 for anthocyanin biosynthesis and FcMS for psoralen synthesis [77]. Haplotype-resolved assemblies reveal evidence of both allele-specific expression associated with fruit ripening and stress response [78].

6.2 Genetic Diversity: Wild vs. Cultivated Populations: Considerable genetic variation has previously been confirmed by similar studies with SSR, ISSR and CDDP markers in both wild and cultivated *F. carica* populations in various areas [79]. The majority of genetic diversity is found within populations rather than among them and polymorphism levels are generally greater than 90% as well as high allelic richness observed within the wild and cultivated groups [80]. Both AMOVA and cluster analysis also always show weak population structure and random genotypes' distribution, respectively suggesting a considerable degree of gene flow between populations and the existence of wide genetic diversity. This rich diversity represents a valuable resource for both breeding, conservation, and adaptation to the environment changes enabling of long-term sustainability and improvement of fig pigmentations [81].

6.3 Functional Genes and Phytochemical Synthesis: The biosynthesis of secondary metabolites such as anthocyanins, coumarins and terpenoids is controlled by structural genes (e.g., FcPAL, FcCHS, FcCHI, FcDFR, FcANS, FcUFGT) that are under tight control from regulatory TFs from the MYB bHLH and WD40 families; these TFs often form a complex of MYB-bHLH-WD40 (MBW) to coordinate tissue-specific and environment-responsive gene expression influencing fruit coloration, nutritional quality and stress tolerance [82,83]. For example, in figs, certain bHLH and MYB genes have been demonstrated to be directly involved in the regulation of anthocyanin biosynthesis, and their expression varies by tissue type as well as environmental factors such as light while WD40 proteins like FcWD40–97 interact with MYB and bHLH partners to form a regulatory complex which demonstrates a sophisticated network that integrates developmental signals with environmental cues to influence phytochemical accumulation [84]

6.4 Genetic Impact on Formulation and Adaptation: Genetic Variation among Fig (*Ficus carica L.*) mutants impacts phytochemical composition, in vitro antioxidant capacity and stress-induced lipid peroxidation potential, ultimately affecting fruit quality traits up to and including phenotypic taste. Phytochemicals, e.g. phenolic and flavonoids, depending on genetic factors like bHLH transcription factor family members, enhance both the fruit quality and tolerance to environmental stress [82]. Local adaptation in wild fig accessions is the accumulation of long-term responses to environmental stress and is crucial for climate change resilience [85,86]. Wild domestic gene flow increases genetic diversity enabling addition of adaptive traits, like drought tolerance or resistance to pest in traditional populations. Genomic resources, including chromosome- level genomes continue to reveal genetic basis of traits such as psoralen biosynthesis and drought tolerance, which could be used in focused breeding [87].

7. RESEARCH GAPS AND FUTURE DIRECTIONS

It is future advanced metabolomics and transcriptomics studies to understand how its multiple bioactive compounds interact, as well as their bioregulation of biosynthesis under diverse environmental stresses. It is very important to standardize the extraction technology and the product form due to its effect on bioavailability, stability, clinical effects of fig-based products. Large-scale clinical studies are necessary to validate traditional medicinal applications and develop novel therapeutic possibilities. Novel delivery systems based on fig polysaccharides and phytochemicals could contribute to the improvement of targeted drug as well as skin care applications.

8. CONCLUSION

Ficus carica continues to be an important and valuable source of rich nutraceutical, therapeutic and eco-adaptative product, as it is strongly characterized by enormous genetic variability and complex secondary metabolite biosynthetic pathways. Its inherent formulation characteristics extend its use to other health, food and personal care markets. Such keen focus research that will add value to traditional knowledge of the plant species with recent molecular and formulation to fully harness its potentials and facilitate crop sustainability in improvement, therapeutic generation as well as for safe drug production.

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Availability of data and materials

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LIST OF ABBREVIATIONS:

ABA- Abscisic Acid
AMOVA- Analysis of Molecular Variance
Bhlh- Basic Helix-Loop-Helix (Transcription Factor Family)
CAL- Cinnamate Ammonia-Lyase
CDDP- Conserved DNA-Derived Polymorphism
CHS- Chalcone Synthase
C4H- Cinnamate 4-Hydroxylase
CoA- Coenzyme A
DNA- Deoxyribonucleic Acid
DFR- Dihydroflavonol 4-Reductase
DMAPP- Dimethylallyl Pyrophosphate
FPP- Farnesyl Pyrophosphate
GPP- Geranyl Pyrophosphate
GGPP- Geranylgeranyl Pyrophosphate

GST- Glutathione S-Transferase
HPLCDAD- High-Performance Liquid Chromatography–Diode Array Detector
IPP- Isopentenyl Pyrophosphate
ISSR- Inter Simple Sequence Repeat
LMP- Low Methoxyl Pectin
MADS- MCM1–AGAMOUS–Deficiens–Serum Response Factor Gene Family
MBW- MYB–bHLH–WD40 Complex
MEP- Methylerythritol Phosphate Pathway
MVA- Mevalonic Acid Pathway
MYB- Myeloblastosis Transcription Factor
NSCLC- Non-Small Cell Lung Cancer
PAL- Phenylalanine Ammonia-Lyase
PCR- Polymerase Chain Reaction
SSR- Simple Sequence Repeat
TPS- Terpene Synthase
UV- Ultraviolet
WD40- Tryptophan Aspartic Acid Repeats Protein Complex

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