

Phytoconstituents to Pharmacology: Mapping the Medicinal Landscape of *Abelmoschus Esculentus*

Kavita Narayan Gaisamudre (Sarwade)¹, Prakash Pralhad Sarwade^{2*}, Mohammed Aashik³, Nuri Farzina Rahman⁴ and Ayush Kamalakar Gaikar⁵

¹Department of Botany, Shriman Bhausaheb Zadbuke Mahavidyalaya, Barshi Tal. Barshi, Dist- Solapur 413401 Maharashtra, INDIA.

^{2*}Associate Professor and Head, Department of Botany, Shikshan Maharshi Guruvarya R. G. Shinde Mahavidyalaya, Paranda Dist. Dharashiv (Osmanabad) 413502, (M.S.) INDIA.

³Department of Pharmaceutics, Desh Bhagat University, Mandi Gobindgarh-147301, Punjab, INDIA.

⁴Assistant Professor, Department of Pharmaceutical Chemistry, The Assam Kaziranga University, Jorhat, Assam-785006, INDIA.

⁵Department of Pharmacy, Bombay Institute of Pharmacy & Research, Next to Lodha Panacea, Near Jain Temple, Bhadra Nagar, Dombivli East 421203 Maharashtra, INDIA.

^{2*}Corresponding Author: ppsarwade@gmail.com



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ABSTRACT

Abelmoschus esculentus (L.) Moench is also called as okra or lady's finger and is an important food and medicinal plant which is widely used in tropical and sub-tropical countries. In addition to its nutritional benefits, the plant also has a variety of bioactive compounds, including flavonoids, phenolic acids, polysaccharides, mucilage, phytosterols, tannins, carotenoids, and other secondary metabolites. The current review compiles the botanical features, ethnomedicinal significance, nutritional profile, phytochemical composition, pharmacological activity and molecular mechanisms of *A. esculentus*. Antioxidant, anti-inflammatory, antidiabetic, antihyperlipidemic, anti-obesity, cardioprotective, hepatoprotective, nephroprotective, gastroprotective, antimicrobial, anticancer, neuroprotective, immunomodulatory, and wound-healing properties have been suggested in the preclinical studies. The effects seem to be multifaceted and involve a variety of interconnected mechanisms such as regulation of oxidative stress, NF- κ B-mediated inflammation, inflammatory cytokines, insulin signalling, AMPK-associated metabolic pathways, lipid metabolism, mitochondrial function, apoptosis, and gut microbiota-related mechanisms. Gastrointestinal protection, metabolic regulation and the potential prebiotic effect are other roles of polysaccharides and mucilage. Though there are some encouraging experimental results, clinical translation is hampered by plant variability in extraction, phytochemical content, dosing, and a lack of pharmacokinetic and human studies. Standardized extracts, identification of marker compounds, mechanistic validation, bioavailability studies, safety studies and clinical trials, should therefore be the focus of future investigations. In conclusion, *A. esculentus* is a promising functional food and phytopharmacological source that can be utilized in the development of nutraceuticals and therapeutic agents.

Keywords- *Abelmoschus esculentus*; okra; phytoconstituents; pharmacological activity; polysaccharides; flavonoids; antioxidant; antidiabetic; signalling pathways; nutraceuticals.

I. INTRODUCTION

1.1 Background and Significance of *Abelmoschus esculentus*

Abelmoschus esculentus (L.) many places of the country, okra (Moench, lady's finger, bhindi or gumbo) is

a vegetable crop that is economically significant and a member of the family Malvaceae. It is widely grown in tropical, subtropical and warm temperate areas including Asia and Africa where it is an important part of the diet. The green, young pods are the most popular edible part of the plant, while its seeds, leaves, flowers, roots and

mucilaginous material are also used in medicine and as food. Because of its high nutritional value, adaptability to various climatic conditions and its wide availability, it has gained importance as food for human consumption and as a source of therapeutic agents due to its production cost [1]. The increasing scientific interest in *A. esculentus* in recent years is due to its rich phytochemical profile. The plant is rich in flavonoids, phenolic acids, polysaccharides, mucilage, sterols, carotenoids, vitamins, minerals and other bioactive components. Flavonoids or polyphenolic derivatives of quercetin are reported as commonly occurring flavonoids and polymers of complex sugars are reported in mucilage that can be related to gastrointestinal and metabolic effects. They have been shown to have antioxidant, anti-inflammatory, antihyperglycemic, lipid-lowering, gastroprotective, antimicrobial, hepatoprotective, nephroprotective, and other biological properties. Due to the rising prevalence of chronic metabolic disorders like diabetes mellitus, obesity, cardiovascular disease, and oxidative stress related disorders, attention has been drawn to the utilization of plant-based functional foods with nutritional and pharmacological properties. In this context, okra is a potential candidate as it is a commonly eaten foodstuff, as well as having a number of biologically active properties that have been proven in the laboratory. Hence, it is of paramount significance to understand the relationship between its phytochemical constituents and its pharmacological effects to assess its possible use in functional foods, nutraceuticals or development of phytopharmaceuticals **Fig.1** [2].



Fig.1: *Abelmoschus esculentus*

1.2 Historical and traditional medicinal relevance

A. esculentus can be used for more than a vegetable. Various parts of the plant have been used in traditional and folk medicine for a long time in different parts of Africa and Asia. Uses include digestive disorders, inflammation, urinary disorders, weakness, respiratory disorders and metabolic disorders. The mucilaginous properties of the pods have been especially responsible for their traditional applications in irritation of the

gastrointestinal tract. The mucilage of okra has been more or less considered as a soothing and protective substance due to its viscous and demulcent nature. Pods or roots have been used to prepare something that calms down the stomach and makes it comfortable. The plant has been used in traditional medicine for its alleged hypoglycemic properties as well, indicating an early understanding of its potential metabolic effects. Some communities have used seeds, as nutritional supplements, and seed extracts as traditional medicines; leaves and flowers have also been utilized in traditional health care [3].

Historically, okra has been used as a food and medicine due to its medicinal properties. Long term dietary exposure may give an indication of both the safety and therapeutic value of such plants which are of particular importance in ethnopharmacology. Experimental explanations have now started to be given for some of these traditional applications. For instance, the antioxidant and anti-inflammatory effects of okra extracts could be the reasons for its traditional applications in inflammatory conditions, whereas the soluble dietary fibre, polysaccharides, and polyphenols may be responsible for the reported role in glucose and lipid metabolism. The composition and biological activity of plant preparations can vary significantly with cultivar, geographic origin, plant part, maturity, extraction method and processing conditions. Thus, traditional knowledge needs to be combined with phytochemical characterization, pharmacological validation, toxicological evaluation, and adequately-designed clinical studies [4].

1.3 Nutritional and therapeutic importance

One of the important nutritional reasons of the widespread dietary importance of *A. esculentus* is its nutritional value. Fresh pods are a source of dietary fibre, carbohydrates, small amounts of protein and fat and a few micronutrients. They are especially useful for their vitamin, mineral and bioactive plant compounds. Okra is also rich in folate, vitamin C, carotenoids, calcium, potassium, magnesium, and other nutritionally important components. The seeds have relatively higher protein and lipid content and may be used as a potential source of nutritional food. Okra also has a lot of mucilage which is a distinguishing feature of okra. The primary constituent of this mucilage was found to be complex polysaccharide, which gives the cooked pods their characteristic viscosity. Soluble fibre and mucilaginous polysaccharides could have a physiological effect on slowing gastrointestinal transit and perhaps both glucose and lipid absorption. The properties have led to studies on the use of okra in controlling diabetes, lowering cholesterol, supporting digestive health, and promoting weight loss [5].

Therapeutic potential of *A. esculentus* is highly related to synergistic effect of its phytochemicals, which includes no single individual. Polyphenols and flavonoids have a scavenging effect on reactive oxygen species and also can modulate the oxidative-stress related pathways, while polysaccharides could affect the immune function,

intestinal function, metabolic homeostasis etc. Experimental studies also indicate that extracts of okra has some regulatory effect on inflammatory mediators, antioxidant defence, protection of hepatic and renal tissues and effect on glucose and lipid metabolism.

With all these good results, however, a lot of evidence is still in its preclinical stages. Comparisons between studies are difficult due to differences in extracts, doses, plant parts and experimental model used. Human clinical studies are still relatively limited and the bioavailability and pharmacokinetics of many of individual okra phytoconstituents are not adequately known. Therefore, new studies should center on the standard extraction method, identification of active marker compounds, mechanism confirmation, assessing safety and clinical trials. The use of these methodologies will be vital for the pharmaceutical exploitation of *A. esculentus* as a nutraceutical and therapeutic agent based on its nutritional and traditional importance [6].

II. BOTANICAL PROFILE OF *ABELMOSCHUS ESCULENTUS*

Abelmoschus esculentus (L.) an important vegetable and medicinal plant of the family Malvaceae, Moench commonly known as okra, lady's finger, bhindi or gumbo. An annual herbaceous warm season crop that is grown widely in tropical and subtropical areas. It is mainly used for the immature edible pods as well as for the leaves, flowers, seeds, roots and mucilage which are also edible and medicinal. There is a high degree of variation in the botanical traits of *A. esculentus* between cultivars, especially plant height, pod shape, colour, pubescence, flowering and maturity period.

Abelmoschus esculentus is part of the Kingdom Plantae, Order Malvales, Family Malvaceae, Genus *Abelmoschus* and species *A. esculentus*. The species was formerly classified in the genus *Hibiscus* and so the species name *Hibiscus esculentus* L. was used, but since then new classification has been based on morphological and reproductive traits, and thus *Abelmoschus* is a new genus. Scientific name: *Abelmoschus esculentus* (L.), is the value used globally. Presently, its use is widespread in botanical, agricultural and pharmacological literature. The plant reaches a height of about 1-2 m, and may reach much greater heights if growing conditions are ideal. Stem erect, stout, cylindrical, often with both fine and coarse hairs. Depending on the cultivar, branching may be limited or extensive. The root system is composed mostly of a strong taproot with many lateral roots that allow the plant to access water and nutrients from the deeper soil layers. It also helps it to adapt to warm conditions, but can be detrimental under drought conditions, particularly in terms of yield and pod quality [7].

Leaves are alternate and on long petioles. The leaves are broad, palmately lobed, and typically with 3-7 lobes with serrated edges. Lobing and leaf size are dependent on the cultivar, stage of growth and

environmental conditions. The leaves are typically green with more or less indumentary. Besides their photosynthetic function, okra leaves are also eaten as vegetables in some parts of the world and studied for their phytochemical and pharmacological properties. *A. esculentus* flowers are big, showy, hermaphroditic and usually solitary in the axils of the leaves. They are similar to those of other members of Malvaceae. Corolla is typically 5 pale yellow or cream-colored petals with a distinct dark reddish or purplish centre of the corolla near its base. The stamens are fused into a staminal column and the ovary is superior and multilocular. Okra is self pollinated with some cross pollination occurring by insect pollination, primarily by bees [9].

After flowering, the fruit is an elongated capsule-like structure that grows quickly. Pods can be green, light green, dark green, reddish or even purple, depending on genotype. They can be cylindrical and smooth, ridged and angular. Immature pods are tender, have mucilage and are generally collected within a couple days post flowering for culinary purposes. As the fruit ripens, the flesh becomes fibrous, and the seeds become numerous and round and are enclosed in longitudinal compartments. Typically they are kidney-shaped, greyish green to dark brown when mature, and are spherical. They are rich in protein, carbohydrates, oil, minerals and bioactives. Okra is grown throughout India, Africa, the Middle East, Southeast Asia and in parts of the Americas. It thrives best in warm climates, generally in fertile, well-drained soils in a good amount of sunlight. The plant is frost- and cold-sensitive, and requires warm climates to thrive well. Due to its wide geographical distribution, morphological variability and adaptability, *A. esculentus* has developed many cultivars, which differ in yield, pod morphology, nutritional composition, and phytochemical content. This plant and genetic variability is especially important in developing medicine as the levels of the pharmacologically active constituents can vary from plant variety to plant variety, and from plant part to plant part. Thus, botanical identification, documentation of cultivar and selection of the appropriate plant material is vital for repeatable phytochemical and pharmacological studies [10].

III. ETHNOBOTANICAL AND TRADITIONAL USES

Abelmoschus esculentus is a plant with a long history of food-crop utilization and as a traditional medicinal plant. It is the most widely cultivated species in Asia, Africa, Middle East and other tropical and subtropical areas, and consequently has many ethnobotanical applications. The leaves, flowers, roots, immature pods and seeds have been employed in traditional medicine and home remedies. These applications are closely linked with the mucilage, dietary fibre, polyphenols, flavonoids, vitamins, minerals, etc. which are also present in the plant. Many of these

traditional uses have since been the subject of scientific investigation, but the level of clinical testing varies. The immature pods of *A. esculentus* are most commonly used. They are eaten in traditional diets as vegetables in boiled, fried, stewed and dried format. They are used as a gastrointestinal tonic with a high mucilage content in gastrointestinal diseases as well. In a few traditional remedies, okra preparations have been used for the management of gastric irritation and constipation and to soothe the stomach discomfort. The mucilaginous polysaccharides in the pods are thought to have demulcent properties through a protective film on irritated mucous membranes. This is a traditional use, consistent with current interest in the gastroprotective and digestive-health properties of okra [11].

Traditionally, okra is also known to be useful for diabetes and other metabolic disturbances. Pods in some community are cut into slivers and put into water to make a mucilaginous liquid that is taken as a remedy at home to reduce high blood glucose. Pod extracts are also used in traditional remedies for metabolic health, as are seed extracts. These practices have encouraged experimental research to elucidate the antihyperglycemic, insulin sensitizing and lipid-lowering effects of *A. esculentus*. Polyphenolic compounds, soluble fibre and polysaccharides have been suggested as key compounds to play a role in these effects due to their potential to modulate intestinal glucose transport, carbohydrate metabolism, oxidative stress, and metabolic signalling.

The roots and leaves of *A. esculentus* have also been used for folk medicine. Leaves used for food; or as decoctions and poultices. They have been traditionally used for inflammatory conditions, as a treatment for pain and for skin complaints. Leaves have been crushed and used externally for wounds, boils and itchy skin at times. These practices are of interest in the field of pharmacology as okra leaves are rich in phenolic compounds and other components that have been documented for their antioxidant, anti-inflammatory, and antimicrobial properties [12].

Pods are not as commonly used as roots but are important in some ethnomedicinal systems. Root decoction and mucilaginous preparations were traditional medicines used as demulcents and for gastrointestinal and urinary irritation. In certain areas, preparations have also been used for respiratory discomfort, and inflammatory complaints. The roots have been investigated less than the fruits and seeds and therefore there is a need to investigate the root phytochemical composition and pharmaceutical activity.

Okra seeds have nutritional and ethnobotanical values. The matured seeds are rich in protein, oil, minerals and polyphenolic compounds, and can be roasted or ground or used in food preparations. In some traditional settings, roasted seeds have been used as a coffee substitute. Preparations made from seeds have also been linked to tonic and nutritional purposes. Some traditional uses of seeds may have a scientific background for their

antioxidant, antihyperlipidemic, and metabolic regulatory properties, as evidenced by the current research.

A. esculentus flowers are less used, but also used in traditional preparations in some localities. They have flavonoids and phenolic compounds, which could be involved in antioxidant activity, like other parts of the plant. Multiple use of plant parts shows that the ethnobotanical value of okra is not limited to its edible pods [13].

In conclusion, the historical medicinal applications of *A. esculentus* offer valuable insights into its potential for modern pharmacological research. Experimental research indicates that there are several ethnomedicinal claims that are supported, such as gastrointestinal protection, glucose regulation, inflammation, and oxidative stress. However, there are different traditional preparations to be used, the dose, plant part used and the duration of use. It is therefore essential to carefully document traditional knowledge and experiences of *A. esculentus*, to standardise the plant chemically, to carry out mechanistic studies, toxicological evaluation and clinical tests under controlled conditions to ensure that traditional usage of the plant can be scientifically validated and used as a therapeutic agent [14].

IV. NUTRITIONAL AND BIOCHEMICAL COMPOSITION

Abelmoschus esculentus is known to be a very popular vegetable and a rich source of nutritional components, exhibiting a notable biochemical diversity. Edible pods, seeds, leaves and other parts of the plants have a wide range of macronutrients, micronutrients, dietary fibre, amino acids, fatty acids, vitamins, minerals and phytochemicals. The composition of okra can vary according to cultivar, geographical origin, maturity stage, farming operations, environmental conditions and post-production treatments. These nutritional and biochemical properties have significant impact on the nutritional value of this product as a functional food, and could serve as the basis for many other reported pharmacological properties. Immature pods have a relatively high moisture content and low energy density and are useful for use in balanced diets. One of the significant nutritional factors are carbohydrates, but a large portion of the carbohydrate fraction comes from complex polysaccharides and dietary fibre sources. Also, okra is a good source of protein, and it contains almost no fat. Its low calorie density and significant fibre content make it a key component in dietary plans focused on weight management, blood sugar control, and heart health [15].

A. esculentus is one of the most significant nutritional characteristics of dietary fibre. The fibre is comprised of soluble fibre and insoluble fibre. The soluble portion is closely linked with the characteristic mucilage of the pods, and the insoluble fibre has the effect of increasing the bulk of the gut and regularity of the

bowel movements. Okra mucilage consists primarily of complex polysaccharides made up of different sugars like galactose, rhamnose and galacturonic acid in different amounts. This mucilage is thick, and can affect gastrointestinal transit and nutrient absorption. It has thus spurred interest in its possible use as a postprandial glucose-lowering agent, as a lipid absorption inhibitor and as a gastrointestinal health aid.

Immature pods are of moderate protein content while the seeds have significantly higher protein content and are considered a potential source of plant based protein. There are several essential and non-essential amino acids in okra seed proteins. The seeds have a nutritional value due to their amino acid composition and have been of interest due to their potential as an alternative protein source. Oil also makes up a significant proportion of the seeds. Okra seed oil mainly consists of unsaturated and saturated fatty acids, such as linoleic acid, oleic acid, and palmitic acid. The seed fraction has additional nutritional value due to the presence of polyunsaturated fatty acids [16].

A. esculentus is also an important source of vitamins. Fresh pods are rich in vitamin C, which is important for antioxidant defence, immune and connective tissue function. Another nutritionally important component is folate, which is especially important to DNA synthesis, cellular division and maternal nutrition. The pods also have provitamin A carotenoids and minor levels of some B-complex vitamins. Their levels can decrease during extended storage or during high-temperature processing, highlighting the need for proper handling and preparation. The mineral content of okra also adds to its nutritional value. Minerals reported throughout the plant include calcium, potassium, magnesium, phosphorus, iron, zinc and manganese. Potassium and magnesium are especially significant for cardiovascular and neuromuscular health; calcium and phosphorus for skeletal health. Iron is involved in oxygen transport and many enzymatic reactions, while zinc and manganese are also factors in many enzymes that are involved in metabolic function and as antioxidant enzymes. The nutritional levels (e.g. mineral concentrations) of pods, leaves and seeds can vary significantly, where the seed may have a comparatively high profile of nutrients [17].

A. esculentus is loaded with biologically active phytochemicals other than nutrients. The most common of the constituents investigated are polyphenolics, flavonoids and phenolic acids. Quercetin and its glycosides are known to be associated with okra along with other glycosidic derivatives of flavonoids. The compounds could be responsible for the antioxidant and anti-inflammatory activity that has been reported for okra extracts. Phenolics are able to act as antioxidants, chelators, and regulators of intracellular signalling pathways involved in oxidative stress and inflammatory responses.

The plant is also rich in biochemical compounds, comprising carotenoids, chlorophylls, sterols, tannins and other minor phytoconstituents. These compounds are of variable relative abundance depending upon the plant part and developmental stage. For instance, the leaves may have more phenolics and pigments in them, while the seeds contain more proteins, lipids and sterol-related compounds. These differences are significant in determining the medicinal characteristics of particular extracts or fractions.

The other important characteristic of okra is its content of antinutritional factors which vary in quantity. Certain minerals can become less bioavailable when present with compounds like phytates, oxalates and tannins at high concentrations. Some of these components can be reduced during common processing methods such as soaking, cooking, fermentation, and thermal processing. Thus, in general, the nutritional properties of okra are significantly better than its antinutrient properties if used as a regular food [18].

It can be concluded that the nutritional and biochemical profile of *A. esculentus* is very similar to its nutritional and medicinal importance. The fibre-rich mucilage, vitamins, minerals, seed proteins, fatty acids and phytochemicals in its composition offer a biochemical foundation for its potential metabolic regulatory, antioxidant, digestive and chronic disease prevention properties. Additional specific nutritional and biochemical standardization and comparison of cultivars and plant parts could enhance the knowledge on the contribution of specific nutritional and biochemical constituents to the pharmacological potential of this versatile species.

V. PHYTOCHEMICAL LANDSCAPE OF *ABELMOSCHUS ESCULENTUS*

Abelmoschus esculentus has a rich phytochemical profile, making it a valuable nutritional and medicinal plant. The plant has various secondary metabolites like flavonoids, phenolic acids, polysaccharides, mucilage, tannins, sterols, terpenoids, carotenoids and trace amounts of other bioactive compounds, present in different parts of the plant including pods, seeds, leaves, flowers and roots. Qualitative and quantitative distribution of these constituents varies with cultivar, plant part, maturity, environment, geographical origin, extraction method, and post harvest processing. The diverse chemical composition supports the antioxidant, anti-inflammatory, antidiabetic, cardioprotective, gastroprotective and other biological activities attributed to okra **Table 1** and **Fig.2** [19].

5.1 Phenolic Compounds

One of the most important classes of bioactive constituents of *A. esculentus* are the phenolic compounds.

They are present all over the plant, but are especially high in pods, seeds and foliage. Different extracts contain phenolic acids like hydroxybenzoic- and hydroxycinnamic-acid derivatives. These compounds make significant contribution to the antioxidant potential of the plant by providing hydrogen atoms or electrons to the ROS and by chelating pro-oxidant metal ions. Hence, the total phenolic content of okra has been often correlated with their free-radical-scavenging activity [20].

5.2 Flavonoids and Flavonoid glycosides

One of the most widely studied phytochemicals of *A. esculentus* is flavonoids. Quercetin and its glycosides have been reported as significant flavonoids. Other compounds related to flavonoids may be found depending on the plant part and/or the analytical method used. The solubility, stability, absorption and biological activity of these molecules are affected by glycosylation. The antioxidant, anti-inflammatory, antihyperglycemic, and vascular protective properties of okra flavonoids have been linked. They can regulate oxidative-stress related enzymes and inflammatory signalling pathways, which is significant in their involvement in the potential therapeutic efficacy of okra in chronic metabolic disorders [21].

5.3 Polysaccharides and Mucilage

The mucilaginous texture of okra is a result of the presence of complex water-soluble polysaccharides. These macromolecules are one of the most unique phytochemicals of the plant. The Okra mucilage is made up of various monosaccharide units arranged in the form of complex polymeric structure such as rhamnose, galactose and galacturonic acid. These polysaccharides have been of interest for their physicochemical properties, especially their water holding capacity and viscosity, for pharmaceutical and nutritional applications. From a biological perspective, okra polysaccharides have been explored for their potential antihyperglycemic, immunomodulatory, antioxidant, gastroprotective, and prebiotic properties. They can thicken the contents of the gastrointestinal (GI) tract, which may help to delay the absorption of glucose and thereby improve postprandial glucose control. Furthermore, mucilage can serve to make natural thickener, stabiliser and/or delivery agent for drugs [22].

5.4 Tannins

Tannins are polyphenolic compounds, which have been identified in different parts of *A. esculentus*, especially in seeds and leaves. These compounds have a protein binding and astringent property and may have antioxidant and antimicrobial activity. It is also possible that tannins affect digestive enzymes and nutrient absorption. While moderate levels of dietary intake can be beneficial, high concentrations can result in less bioavailability of proteins and minerals. The activity of okra thus depends on its concentration, plant part and its method of preparation.

5.5 Terpenoids and Sterols

Terpenoid and phytosterol constituents are also found in okra. Structurally, plant sterols resemble cholesterol, and can be involved in the plant's ability to lower lipids by blocking cholesterol absorption in the gut. The seed fractions rich in sterols, therefore, have been the subject of study with regard to dyslipidemia and cardiovascular protection. Terpenoid compounds are less well-studied than flavonoids and polysaccharides, but can be involved in antioxidant, anti-inflammatory, and antimicrobial effects.

5.6 Carotenoids and Pigments

The green pods and leaves of *A. esculentus* contain the majority of carotenoids. These pigments also contain provitamin A and non-provitamin A carotenoids which have antioxidant effects and are important for nutrition. The chlorophylls are also present in large amounts in green tissues and give the green colour to fresh pods and leaves. Concentrations of pigment vary from cultivar to cultivar, as well as depending on storage, maturity and cooking. Carotenoids could provide antioxidant effects that are synergistic with the antioxidant activity of the phenolic compounds/flavonoids [23-25].

5.7 Other Minor Phytoconstituents

Besides the major groups mentioned above, okra contains other low molecular weight components such as organic acids, saponins, amino-acid derivatives, volatile compounds, etc. Bioactive peptides and seed-associated compounds with potential antioxidant and/or metabolic activity have also been identified in some studies. Though they may occur in small amounts, they may interact additively or synergistically to add to the biological activity associated with them.

The phytochemical profile varies greatly between the different parts of *A. esculentus*. The pods have a higher mucilage, soluble polysaccharide, phenolics, and flavonoids content while seeds have more proteins, oils, sterols, and some phenolics. Leaves usually contain high amounts of flavonoids, pigments, and antioxidants, and the flowers can have more phenolic and flavonoid derivatives. The metabolites of roots are comparatively less studied and also have biologically relevant metabolites [26].

In general, the phytochemical profile of *A. esculentus* is highly complex and diverse. The pharmacological activity does not seem to be reliant on a single active compound but rather, on the synergistic effect of multiple classes of phytoconstituents. So, a thorough phytochemical profiling, quantitative standardization and marker compound characterization are therefore indispensable for establishing reliable correlations between chemical composition and therapeutic activity.

Table 1: Major phytoconstituents identified in different parts of *Abelmoschus esculentus*

Phytochemical class	Major reported phytoconstituents/examples	Potential biological relevance
Flavonoids	Quercetin, quercetin-3- <i>O</i> -gentiobioside, quercetin-3- <i>O</i> -glucoside (isoquercitrin), quercetin-3- <i>O</i> -rutinoside (rutin)	Antioxidant, anti-inflammatory and metabolic regulatory potential
Flavan-3-ols	Catechin and catechin derivatives	Antioxidant and cytoprotective properties
Phenolic acids	Protocatechuic acid and other phenolic-acid derivatives	Free-radical scavenging and modulation of oxidative stress
Anthocyanins	Cyanidin 3-sambubioside and delphinidin 3- <i>O</i> -sambubioside	Antioxidant and pigment-related biological properties
Carotenoids	α -Carotene, β -carotene and lycopene	Antioxidant activity and nutritional importance
Polysaccharides/mucilage	Polymers containing rhamnose, galactose, galacturonic acid, glucose, arabinose, mannose and related sugars	Gastroprotective, metabolic, prebiotic and functional-food potential
Flavan-3-ols	Catechin and epicatechin	Antioxidant and cytoprotective activity
Procyanidins	Procyanidin B1 and procyanidin B2	Potent polyphenolic antioxidant activity
Flavonoid glycosides	Quercetin glycosides, including quercetin-3- <i>O</i> - β -glucopyranosyl-(1 $\rightarrow$ 6)-glucoside	Antioxidant and metabolic effects
Fatty acids	Linoleic acid, oleic acid and palmitic acid	Nutritional value and possible influence on lipid metabolism
Flavonoids/polyphenols	Catechin, flavonol glycosides and other phenolic constituents	Antioxidant, anti-inflammatory and metabolic activities
Polysaccharides	Polysaccharides containing arabinose, xylose, glucose, mannose and galactose	Potential antioxidant, immunomodulatory and functional properties
Polysaccharides	Galactose-, rhamnose- and galacturonic-acid-containing polysaccharides	Potential antioxidant and immunomodulatory effects
Flavonoids	Flavonol glycosides	Possible antioxidant and pharmacological contribution
Carbohydrates/polysaccharides	Carbohydrate-rich and mucilaginous constituents	Relevant to traditional demulcent applications
Phytosterols	β -Sitosterol, stigmasterol and daucosterol	Potential cholesterol-lowering, anti-inflammatory and membrane-modulating properties
Terpenoid/sterol derivatives	Multiple sterol and terpenoid derivatives	May contribute to the broader pharmacological profile of the plant
Tannins	Condensed and other tannin-type polyphenolic constituents	Antioxidant, astringent and antimicrobial potential
Miscellaneous metabolites	Organic acids, volatile constituents and nitrogen-containing metabolites	May provide additional or synergistic biological effects

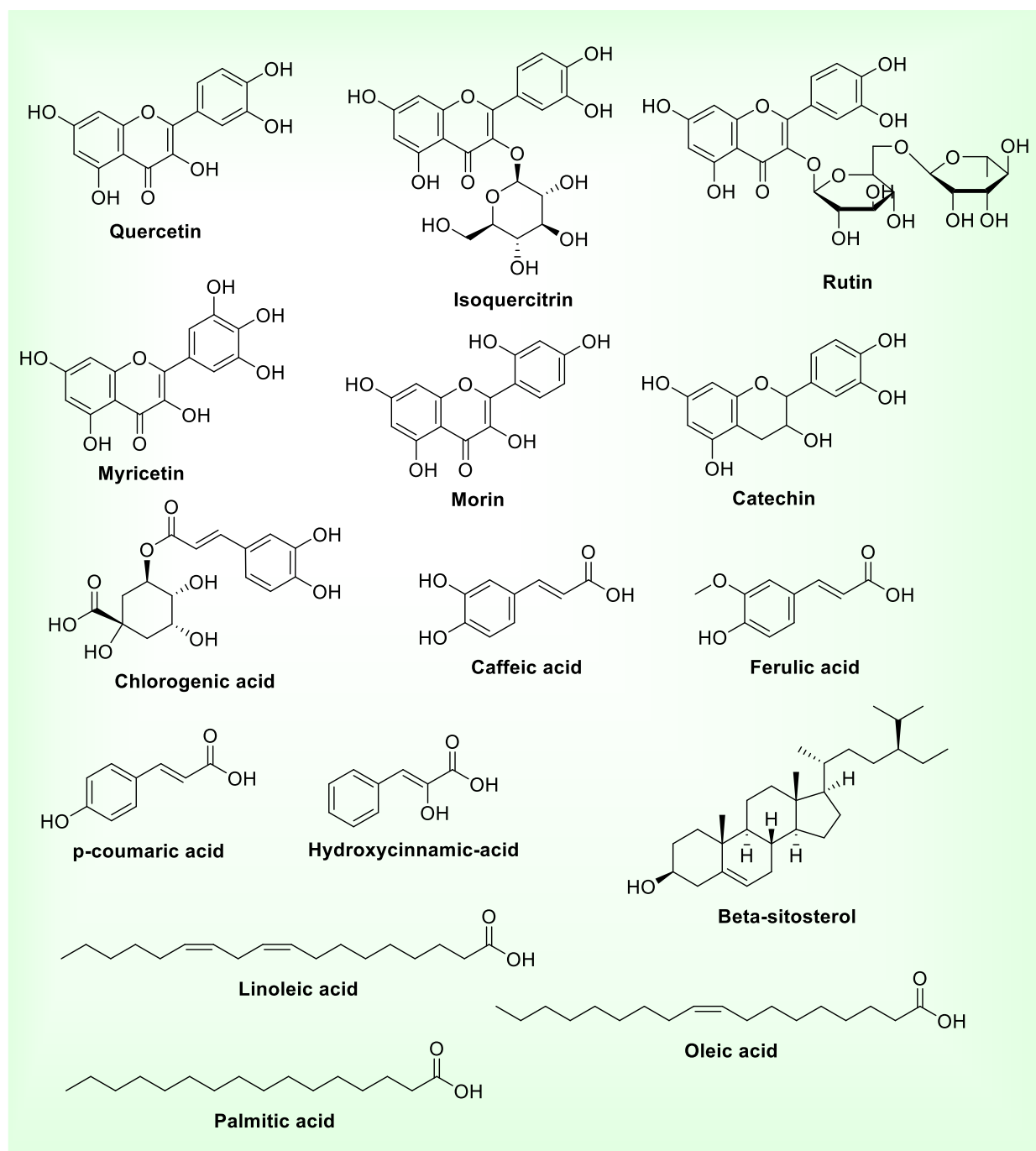


Fig.2: Major Phytoconstituents present in *Abelmoschus esculentus*

VI. PHARMACOLOGICAL ACTIVITIES

The diverse phytochemical constituents of *Abelmoschus esculentus* have caught a lot of pharmacological attention due to the flavonoids, phenolic acids, polysaccharides, mucilage, sterols, tannins, carotenoids, and other bioactive constituents present in it. Experimental investigation with various parts of okra, extracts, fractions and isolated compounds revealed that okra displays wide spectrum of biological activity. The

effects are mostly associated with modulation of oxidative stress, inflammatory signalling, glucose and lipid metabolism, cellular defence mechanisms, tissue protection mentioned in **Table 2** [27].

6.1 Antioxidant activity

The antioxidant activity is one of the consistently reported pharmacologic properties of *A. esculentus*. Pod extracts and extracts from the pods and seeds have shown free radical scavenging and reducing properties in various experimental systems, while extracts from the pods and leaves have yielded the same activity in the leaf. Pod

extracts and extracts from the pods and seeds have exhibited free radical scavenging and reducing properties in various experimental systems while extracts from pods and leaves have exhibited the same activity in the leaf. The flavonoids, phenolic acids, carotenoids and other polyphenolic compounds are responsible for these effects. Quercetin derivatives and related phytochemicals can scavenge the ROS and inhibit the lipid peroxidation. The antioxidant defence system of the body was also reported to be improved in the case of okra extracts which have been observed to increase the activity of antioxidant enzymes like superoxide dismutase, catalase and glutathione-related system. These mechanisms suggest that *A. esculentus* could offer a therapeutic benefit to prevent oxidative damage to cells and tissues in metabolic, inflammatory, hepatic, renal, and neurodegenerative diseases [28].

6.2 Anti-inflammatory activity

The anti-inflammatory effect of okra seems to be related to its antioxidant phytochemicals and polysaccharides. The results of the experimental studies indicate that *A. esculentus* extracts could inhibit the production of pro-inflammatory mediators and cytokines such as tumor necrosis factor- α , interleukin-1 β , and interleukin-6. These effects may be mediated by NF- κ B pathway inhibition. The anti-oxidative and anti-inflammatory effects of okra can help protect against chronic low-grade inflammation, which is associated with diabetes, cardiovascular disease, obesity, and tissue damage [29].

6.3 Antidiabetic and antihyperglycemic activity

One of the most widely studied medicinal properties of *A. esculentus* is its antidiabetic effects. The glucose lowering activity has been demonstrated in experimental models of diabetes with pod, peel, seed extract and whole fruit extracts. There are a number of processes that could account for this activity. Soluble fibre, mucilage, and polyphenols can help to increase the viscosity of the intestines and slow down the absorption of glucose, whereas polyphenols may inhibit enzymes that break down carbohydrates, like alpha-amylase and alpha-glucosidase. The phytochemicals present in okra can also help in enhancing insulin sensitivity, utilize glucose more efficiently in peripheral tissues and help lower oxidative damage in the peripheral and pancreatic tissues. All these may indicate the potential of okra to be used as a functional food ingredient for glycemic management, but further clinical investigations are required [30].

6.4 Antihyperlipidemic activity

In a few experimental studies, okra has been shown to have lipid-lowering effect. Okra extracts or dietary supplements have been linked with lower total cholesterol, triglycerides, and low-density lipoprotein cholesterol levels, and perhaps higher high-density lipoprotein cholesterol levels. Soluble fibre may bind bile acids and cholesterol in the gut, which could decrease their absorption and increase their elimination.

Polyphenols can also modulate hepatic lipid metabolism and phytosterols can inhibit cholesterol absorption in the gut. These actions may account for the potential role of *A. esculentus* for dyslipidaemia and cardiovascular risk reduction [31].

6.5 Anti obesity activity

Due to the fibre content of okra, combined with its metabolic bioactives, it has been the topic of research for its anti-obesity effects. Dietary fibre may be beneficial in making the person full, slowing stomach emptying, and preventing over-consumption of energy. Experimental models have shown that extracts from okra have been linked to an improvement in body weight gain, glucose metabolism, lipid accumulation, and insulin resistance. Other contributing factors may be activation or modulation of metabolic pathways related to fatty-acid oxidation and energy homeostasis. Thus, *A. esculentus* could affect more than just obesity, and therefore, the mechanism of action for obesity remains a mystery [32].

6.6 Cardioprotective activity

The cardioprotective efficacy of okra may be linked to its antioxidant and anti-inflammatory, antihyperlipidemic and metabolic effects. Endothelial dysfunction and cardiovascular damage are important consequences of oxidative stress and inflammation, and phytochemicals found in okra could help to inhibit these. There is potential for further reduction of cardiovascular risk through improvement of lipid profile and glycemic control. Experimental results have also indicated protection against oxidative myocardial damage, and preservation of endogenous antioxidant enzymes. Taken together these effects may be used to further explore the potential of okra as a therapeutic functional food for the cardiovascular system [33].

6.7 Antihypertensive activity

Initial research shows that *A. esculentus* might be helpful with lowering blood pressure. This effect could be attributed to endothelial function, antioxidant activity, modulation of vascular tone and the content of potassium and other nutritionally relevant minerals. Some bioactive peptides and phytochemicals could also have a role in the regulation of blood pressure enzymes. The antihypertensive evidence is not as comprehensive as for antidiabetic and antioxidant effects, however, and there is a need for additional mechanistic and clinical investigations [34].

6.8 Hepatoprotective activity

The hepatoprotective activity of okra extract has been demonstrated in the experimental models of chemical and metabolic induced liver damage. It has been linked to decreased liver enzyme abnormalities, lipid peroxidation, oxidative stress and inflammatory changes. The flavonoids and phenols could have a beneficial effect in protecting hepatocyte membranes and enhancing endogenous antioxidant defence, whereas the polysaccharides could provide further anti-inflammatory properties. The mechanisms indicate that *A. esculentus* might have a protective role in the reduction of

hepatotoxicity induced by toxins, metabolic dysfunction and oxidative stress [35].

6.9 Nephroprotective activity

The nephroprotective activity of okra has also been studied especially in diabetes, in oxidative stress and toxicant induced renal injuries. Okra preparation can decrease oxidative damage, increase the antioxidant enzyme activity, and restrain inflammatory injury in renal tissues. Better blood glucose and lipid metabolism may also help to minimize secondary renal stresses in metabolic disorders. Others report biochemical parameters of renal function may be normalised after treatment with okra extracts.

6.10 Anti-inflammatory activity

The mucilage of *A. esculentus* is a potent justification for the use of this plant traditionally in the gastrointestinal system. The viscous polysaccharides may coat and protect the mucous membranes and may help to maintain the integrity of the mucous membrane, possibly lessening the irritation. Experimental research indicates that okra preparations can help alleviate gastrointestinal inflammation, exert antioxidant effects and reduce gastric damage. Polyphenols can also play a role by helping to reduce oxidative stress and promote tissue repair. These co-operative effects can serve as a logical basis for gastroprotective and anti-ulcer effects [36].

6.11 Antimicrobial activity

The various extracts of okra exhibited antimicrobial activity against some bacterial species. The products of secondary metabolism (phenolic compounds, flavonoids, tannins) can interact with the bacterial cell membranes, enzymes or metabolic processes. Antimicrobial activity has been found to be variable as per plant part, solvents, concentration and microbial strains tested. The results suggest a potential, but okra cannot be recommended as a stand-alone treatment at this time as an alternative to proven antimicrobial treatment [37].

6.12 Antifungal activity

Extracts of several *A. esculentus* species have also been reported to have antifungal properties. Bioactive compounds could act against the fungi by affecting the integrity of the membrane or the metabolic processes. The extracts from the seed and leaves have been attracting special interest in preliminary screening studies. Evidence is, however, relatively scarce and detailed characterization of antifungal constituents and their mechanism is needed for therapeutic significance [38].

6.13 Anticancer and cytotoxic activity

Okra has anticancer potential, selected cancer cell models demonstrated cytotoxic or growth inhibitory effects of extracts and isolated phytoconstituents. The proposed mechanisms are induction of apoptosis, inhibition of cell proliferation, regulation of oxidative stress, and inhibition of the survival signalling pathways of cancer cells. Some lectin-like proteins and polyphenolic compounds are also potentially interesting for their anti-proliferative properties. But the data in most

instances are restricted to in vitro or early preclinical investigations, and definite conclusions about clinical anticancer activity are not yet possible [39].

6.14 Neuroprotective activity

The antioxidant and anti-inflammatory properties are likely to be the mechanism of action behind the neuroprotective effects of okra. Several neurological disorders are characterized by oxidative stress, mitochondrial dysfunction and neuroinflammation. The phytochemicals present in okra can help maintain the integrity of neural cells by lowering the levels of reactive oxygen species and also by encouraging the normal antioxidant mechanisms. With better metabolic control, indirectly benefits to the neurological system may also occur, especially in diabetes associated cognitive dysfunction. However, the study of *A. esculentus* for its neuroprotective effects is still in an early stage of development [40].

6.15 Immunomodulatory activity

Immune-modulatory properties of polysaccharides and polyphenolic constituents of okra have been studied. These compounds could alter the activities of macrophages, cytokine production and cellular immune responses. Okra polysaccharide can augment protective immune activity in some experiments, and diminish excess inflammatory signalling in others. Dual regulatory effects are of interest in conditions where there is immune imbalance, but the characterization of the specific active molecules should be continued [41].

6.16 Wound-healing activity

The wound healing property of *A. esculentus* might be attributed to its antioxidant, anti-microbial, anti-inflammatory and mucilage properties. Leaves, pods or mucilage can be used to make topical treatments that can help keep the skin moist, prevent skin damage and promote skin repair. The antioxidant activity can decrease the oxidative damage at the wound site while antimicrobial activity can help to prevent microbial proliferation. Experimental observations indicate that there are wound contraction and tissue regeneration improvements, but that standardised formulations and clinical evaluation are required [42].

6.17 Reproductive and fertility-related effects

The effects of okra on reproductive function are not so well understood and may vary by part of the plant, dose, duration and experimental model. Its actions on reproductive hormones, sperm characteristics, oxidative stress and reproductive-organ function have been investigated in some studies. The antioxidant components could help to prevent oxidative damage to the reproductive tissues, while the nutritional components could aid in normal physiological function. On the other hand, reports on concentrated extracts emphasize the importance of careful assessment of reproductive safety. Thus, reproductive and fertility effects should be approached with some caution until further uniform mechanistic and toxicological data are available [43].

The overall profile of the drugs produced by *A. esculentus* is an effect of its polyphenols, flavonoids, polysaccharides, sterols, fibre, and other phytochemicals. Several other activities are supported mainly by preliminary preclinical evidence, while the antioxidant, anti-inflammatory, antidiabetic and lipid-regulating effects are best supported. Standardized extracts, identified marker compounds, dose response relationships, Pharmacokinetics and clinical studies with well designed design should be overlooked in future research to identify which of these pharmacological properties can be exploited in therapeutic and nutraceutical applications [44].

VII. MOLECULAR MECHANISMS AND SIGNALLING PATHWAYS

The pharmacologic effects of *Abelmoschus esculentus* are currently linked to regulation of several molecular targets instead of one single target. The phytochemicals, such as flavonoids, phenolic acids, polysaccharides, mucilage-derived carbohydrates, sterols and others can affect oxidative stress, inflammation, glucose and lipid metabolism, mitochondrial function, apoptosis, and intestinal microbial balance. This multi-target behaviour is especially significant in chronic diseases, like diabetes, obesity, cardiovascular diseases, inflammatory diseases and cancer, where multiple intertwined signalling networks play a role in the evolution of the disease [45].

7.1 Regulation of Oxidative Stress and the Nrf2/HO-1 Pathway

Oxidative stress is the imbalanced production of ROS and the endogenous antioxidant defence. Phytoconstituents from *A. esculentus* such as polyphenols and flavonoids might help prevent oxidative damage by directly scavenging free radicals and/or by regulating antioxidant mechanisms within the cells. One of the key mechanisms is the transcription factor nuclear factor erythroid 2-related factor 2 (Nrf2) which regulates the expression of antioxidant and cytoprotective genes. In the presence of oxygen, activation and nuclear translocation of Nrf2 activate genes that encode enzymes, including heme oxygenase-1 (HO-1), superoxide dismutase, catalase, glutathione-related enzymes and NADPH quinone oxidoreductase-1. The phytochemicals present in okra may help enhance this line of defence, which can alleviate lipid peroxidation, protein oxidation, and cellular damage. The hepatoprotective, nephroprotective, cardioprotective and neuroprotective effects of *A. esculentus* have been reported, which in part could be attributed to the enhancement of the Nrf2/HO-1 pathway [46].

7.2 Modulation of NF- κ B-mediated inflammation

Nuclear factor-kappa B (NF- κ B) is a key player in inflammatory responses and acts as a regulator of the

transcription of many genes that regulate cytokine production, immune-cell activation and tissue injury. Increased and sustained NF- κ B activation has been linked to chronic inflammatory diseases, insulin resistance, obesity, cardiovascular disease, and carcinogenesis. The polyphenolic and flavonoid profile of okra can help to inhibit overactive activation of NF- κ B by inhibiting upstream oxidative signals and disrupting inflammatory signalling pathways. The decreased activity of NF- κ B may then lead to a decrease in the expression of inflammatory mediators including cyclooxygenase-2, inducible nitric oxide synthase and a number of pro-inflammatory cytokines. This mechanism establishes an important connection between antioxidant and anti-inflammatory properties of *A. esculentus*, since the antioxidant activity can indirectly help to decrease inflammation [47].

7.3 Effects on inflammatory cytokines

Chronic inflammation and metabolic dysfunction are regulated by inflammatory cytokines, namely tumour necrosis factor (TNF)- α , interleukin (IL)-1 β and IL-6. These mediators can prevent insulin action, injure the endothelial cells, cause inflammation in the liver and lead to tissue damage when present in excess amounts. Experimental studies indicate that okra extracts might suppress the production/activation of these cytokines. The effects can be due to the inhibition of NF- κ B and other inflammatory pathways along with a decrease in oxidative stress. Macrophage activation and immune signalling may also be affected by the polysaccharide. *A. esculentus* has the capability of decreasing the activity of pro-inflammatory cytokines, thereby creating a more balanced inflammatory environment in metabolic and inflammatory diseases [48].

7.4 Regulation of glucose metabolism and insulin signalling

The anti-diabetic effect of *A. esculentus* seems to be involved in both gastrointestinal and intracellular pathway. Soluble fibre and mucilage in the pods may lead to slower gastric emptying and slow down the absorption of glucose in the intestine. Besides, some phytochemicals could inhibit the activity of carbohydrate-digesting enzymes like α -amylase and α -glucosidase, which could help lower the postprandial glucose level. The okra-derived compounds might enhance insulin sensitivity and facilitate the uptake of glucose in peripheral tissues at the cellular level. This could include the regulation of insulin receptor signalling and the downstream pathways like phosphatidylinositol-3-kinase/protein kinase B (PI3K/Akt), which is crucial for the translocation of the glucose transporters and glucose utilization. The reduction of oxidative stress and inflammatory cytokines could further enhance insulin signalling, as both are important factors in insulin resistance [49].

7.5 AMPK-mediated metabolic regulation

AMP-activated protein kinase (AMPK) acts as a key energy sensor and a central regulator of energy metabolism in response to cell energy needs. AMPK promotes glucose uptake, fatty acid oxidation, mitochondrial energy production, and inhibits fatty-acid synthesis and hyperglucconeogenesis. Concentrations of bioactive compounds in *A. esculentus* could potentially modulate the AMPK-related pathways, especially in cases of obesity, insulin resistance, and metabolic stress. AMPK activation has the ability to reduce hepatic glucose production, increase insulin sensitivity and inhibit enzymes responsible for the synthesis of fatty-acids and cholesterol. It is hypothesised that these mechanisms may be responsible for the reported anti-obesity, anti-hyperglycaemic and anti-hyperlipidemic activity of okra. However, the direct evidence of the individual okra phytoconstituents acting as AMPK activators is still not well understood and needs to be studied in detail [50].

7.6 Modulation of lipid metabolism

The anti-lipid activity of *A. esculentus* occurs in both the gut and liver. Soluble dietary fibre will chelate bile acids and inhibit cholesterol absorption in the intestine, which will help to promote cholesterol excretion. Phytosterols also can be inhibitory to the absorption of dietary cholesterol. Okra phytochemicals could act at a metabolic level to affect pathways of lipid synthesis, fatty-acid oxidation, and lipoprotein metabolism. AMPK mediated regulation can potentially inhibit lipogenic enzymes, while enhanced insulin sensitivity may help to decrease abnormal liver lipid accumulation. Antioxidants can also help prevent low-density lipoprotein (LDL) from oxidizing, a factor in atherosclerosis. These synergistic effects suggest that okra can have a beneficial effect on the circulating lipid profile and decrease the metabolic stress of dyslipidemia [51].

7.7 Apoptosis and cell-cycle regulation in cancer

Early research indicates that some of the compounds found in *A. esculentus* can interfere with the growth of cancer cells, helping to induce cell death and disrupt the cell cycle. Controlled apoptosis is regulated by the balance between pro-apoptotic and anti-apoptotic proteins, the integrity of the mitochondria, activation of caspases and some intracellular signalling pathways. The flavonoids, phenolics and proteinaceous constituents in okra have been studied for their potential against inhibiting the viability of cancer cells. The mechanisms suggested are enhancement of pro-apoptotic signalling, activation of caspases, disruption of the mitochondrial membrane and modulation of Bcl-2 family proteins. Other extracts can also affect the cell-cycle checkpoints and decrease the progression through the proliferative stages. Blocking inflammatory and oxidative signalling may yield further anti-cancer benefits, particularly in cases of NF- κ B and associated pathways survival of

tumour cells. They are rather preliminary results and should be viewed as a proxy for clinical anticancer efficacy [52].

7.8 Mitochondrial protective mechanisms

The mitochondria play a key role in energy production, oxidative metabolism, apoptosis and cellular stress responses. An excess of ROS may cause damage to the cell's DNA, protein and mitochondrial membranes, resulting in decreased ATP production and cell death. Mitochondrial dysfunction is responsible for diabetes, cardiovascular disease, hepatic injury, renal dysfunction and neurodegeneration. The antioxidant properties of *A. esculentus* could help prevent oxidative damage and maintain the integrity of mitochondrial membrane functions. The boosting of endogenous antioxidant defense can help lower the generation of ROS in mitochondria, and the improvement of metabolic regulation can help lower excess substrate overload. Mitochondrial function preservation can be therefore responsible for the tissue protective effect of okra noted in experimental models. The interconnected nature of these mechanisms is seen from the fact that activation of Nrf2, AMPK signalling and inhibition of inflammatory pathways are all interconnected with mitochondrial regulation [53].

7.9 Gut microbiota related mechanisms

The gut microbiota plays an important role in regulating metabolic, immune and inflammatory health, and is now a well-recognized factor. The indigestible polysaccharides and dietary fibre in *A. esculentus* can reach the colon where they can be used as substrates for microbial fermentation. This makes it likely that okra has some biological effects that occur in a prebiotic-like manner. The fermentation of fibre can lead to the generation of short-chain fatty acids like acetate, propionate and butyrate that affect intestinal barrier function, glucose metabolism, modulation of immune system and energy balance [54]. It is also possible that okra polysaccharides could change the relative abundance of good and bad bacteria. New bacterial balance can help decrease intestinal inflammation, endotoxin-induced metabolic stress and maintain mucosal integrity. These gut mediated effects of okra may account, in part, for its antidiabetic, anti-obesity, and anti-inflammatory effects. In general, the molecular pharmacology of *A. esculentus* seems to be a complex interplay between various antioxidant, inflammatory, metabolic, mitochondrial, and apoptotic pathways and gut microbiota-related pathways. Many of the biological effects have been reported and might be explained by activation of Nrf2-mediated antioxidant defence, inhibition of NF- κ B signalling, regulation of inflammatory cytokines, improvement of insulin and AMPK pathways, modulation of lipid metabolism and protection of mitochondrial function [55].

Table 2: Molecular targets and signalling pathways associated with major pharmacological effects of *Abelmoschus esculentus*

Pharmacological effect	Major molecular target/signalling pathway	Principal molecular/biochemical changes	Major associated constituents	Biological consequence
Antioxidant	Nrf2/ARE–HO-1 antioxidant axis	↑ endogenous antioxidant defence; ↑ SOD, CAT, GPx and GSH; ↓ ROS and lipid peroxidation	Flavonoids, phenolic acids, polyphenols, polysaccharides	Improved cellular redox balance and protection against oxidative injury
Anti-inflammatory	TLR4/NF-κB signalling	↓ TLR4 activation and NF-κB nuclear translocation; reduced inflammatory mediator production	Okra polysaccharides, flavonoids and phenolics	Suppression of chronic and tissue-specific inflammatory responses
Cytokine regulation	NF-κB/MAPK-associated inflammatory networks	↓ TNF-α, IL-1β and IL-6; modulation of anti-inflammatory cytokines such as IL-10	Polysaccharides and polyphenolic compounds	Reduction of inflammatory-cell activation and tissue injury
Antidiabetic / antihyperglycemic	PI3K/Akt and insulin-signalling pathways	Improved insulin responsiveness and glucose utilization; modulation of β-cell survival-related pathways	Polysaccharides, quercetin derivatives, flavonoids and soluble fibre	Improved glycemic control and reduced insulin resistance
β-cell protection	PI3K/mTOR/GLP-1R-related signalling	↑ PI3K, mTOR and GLP-1R-associated signalling; ↓ Bax and caspase-related apoptosis in experimental systems	Okra-derived bioactive fractions	Preservation of pancreatic β-cell viability and function
Carbohydrate digestion	α-Amylase and α-glucosidase inhibition	Reduced enzymatic breakdown of complex carbohydrates and slower intestinal glucose availability	Polyphenols, flavonoids and fibre-rich fractions	Attenuation of postprandial hyperglycemia
Metabolic regulation	AMPK-associated energy-sensing pathway	Regulation of glucose utilization, fatty-acid oxidation and energy metabolism	Polyphenols, flavonoids and polysaccharides	Improved metabolic homeostasis and insulin sensitivity
Anti-hyperlipidemic	AMPK/lipogenesis-related pathways; intestinal bile-acid/cholesterol handling	↓ TC, TG and LDL; reduced lipid accumulation; increased cholesterol/bile-acid elimination	Soluble fibre, mucilage, phytosterols and polyphenols	Improvement in dyslipidemia and hepatic lipid homeostasis
Anti-obesity	AMPK-associated metabolic regulation	Increased fatty-acid utilization; reduced abnormal lipid storage and metabolic stress	Polysaccharides, flavonoids and dietary fibre	Reduced metabolic dysfunction associated with obesity
Hepatoprotective	Oxidative stress–inflammation axis; gut–liver signalling	↓ MDA, TNF-α and other inflammatory mediators; ↑ SOD/CAT; improvement of hepatic biochemical markers	Pectic polysaccharides, flavonoids and phenolics	Reduced hepatocyte injury, oxidative stress and inflammation
Nephroprotective	Antioxidant and inflammatory signalling networks	Reduced ROS/lipid peroxidation and inflammatory injury; restoration of endogenous antioxidant systems	Polyphenols, flavonoids and polysaccharides	Preservation of renal structure and function

Cardioprotective	Oxidative stress, inflammatory and lipid-regulatory pathways	Reduced oxidative damage and dyslipidemia; improved antioxidant status	Flavonoids, polyphenols, phytosterols and fibre	Protection against metabolic and oxidative cardiovascular injury
Gastroprotective	Mucosal antioxidant and anti-inflammatory mechanisms	↓ mucosal oxidative damage, inflammatory infiltration and apoptosis; improved epithelial regeneration	Mucilage, pectic polysaccharides, flavonoids and phenolics	Preservation of gastric mucosal integrity and reduced ulcer formation
Anticancer / antiproliferative	Intrinsic apoptotic pathway	↑ Bax/Bcl-2 ratio, caspase-9 and caspase-3; enhanced apoptosis	<i>A. esculentus</i> lectin and polyphenolic constituents	Selective inhibition of cancer-cell proliferation and induction of programmed cell death
Cell-cycle regulation	p21-associated checkpoint regulation	↑ p21 expression and suppression of uncontrolled cell-cycle progression	Okra lectin and potentially other bioactive constituents	Reduced proliferation of susceptible cancer cells
Mitochondrial protection	Mitochondrial redox and apoptosis pathways	↓ mitochondrial ROS and membrane injury; preservation of antioxidant defence and energy metabolism	Flavonoids, phenolics and polysaccharides	Maintenance of mitochondrial integrity and reduced cellular injury
Neuroprotective	TLR4/NF-κB–neuroinflammatory and antioxidant pathways	↓ neuroinflammatory signalling and cytokines; attenuation of oxidative stress	Okra polysaccharides, seed polyphenols and flavonoids	Protection against cognitive and neuronal dysfunction
Gut–brain axis modulation	Microbiota–TLR4/NF-κB signalling	Alteration of gut microbial composition and SCFAs; reduced systemic and hippocampal inflammation	Non-digestible okra polysaccharides	Potential improvement in stress-related and neurobehavioral dysfunction
Gut microbiota modulation	Microbiota–SCFA–intestinal barrier axis	↑ beneficial bacterial populations and SCFA production; improved microbial balance	Pectic and other non-digestible polysaccharides	Improved intestinal, metabolic and inflammatory homeostasis
Intestinal barrier protection	Tight-junction/MAPK-associated signalling	↑ Claudin-1 and Occludin; modulation of MAPK signalling	Pectin-rich polysaccharide fractions	Strengthening of epithelial barrier integrity
Immunomodulatory	MAPK and microbiota–immune signalling	Modulation of cytokines, immunoglobulins and CD4 ⁺ /CD8 ⁺ balance	Pectin-based polysaccharides	Restoration or regulation of cellular and humoral immune responses

VIII. FUTURE PERSPECTIVES

The scientific interest of the *Abelmoschus esculentus* increases, due to its functional food, nutraceutical and pharmacologically active properties. Future work should go beyond extract based work to identification, isolation and standardization of specific bioactive constituents that brings about the biological

effects of the plant. Flavonoids, phenolic compounds, polysaccharides, mucilage, phytosterols and bioactives derived from the seeds are of particular consideration. The relations between phytoconstituents and molecular targets could be more precisely established by applying advanced analytical approaches such as metabolomics, LC-MS/MS, molecular docking, network pharmacology and systems biology. Standardisation is still a major demand for

translational development. The phytochemical profiles and the pharmacologic effects can significantly differ based on cultivar, geographical origin, maturity, plant part, extraction solvent and processing conditions. Therefore, future research needs to establish chemical marker compounds and use validated quality control procedures to guarantee the reproducibility of the batches. Pharmacokinetic and bioavailability studies are also needed to see if the levels that result in biological effect in experimental models can be achieved in humans. The gut microbiota is also an interesting potential research target, as okra contains high levels of dietary fibre and complex polysaccharides, which could have a prebiotic effect. Research that combines microbiome and metabolomics may help shed light on the connection between eating okra, microbial metabolites, and metabolic health. Other innovative delivery systems such as nanoformulations and polysaccharide based carriers could help further enhance the stability and bioavailability of some phytoconstituents. Most importantly, well designed randomized controlled clinical trials are required for establishing the reported antidiabetic, antihyperlipidemic, anti-inflammatory, cardioprotective and other therapeutic effects. Long term safety, optimization of dose, herb/drug interactions, and effects in specific patient populations should also be explored. This cross-disciplinary research will help translate *A. esculentus* from a traditional food crop to clinical use as a nutraceutical and/or phytopharmaceutical.

IX. CONCLUSION

Abelmoschus esculentus is a valuable medicinal and nutritive plant containing wide range of phytochemicals and pharmacologic activities. It bears various constituents such as flavonoids, phenolic acids, polysaccharides, mucilage, phytosterols, carotenoids, tannins and other bioactive molecules in its pods, seeds, leaves, flowers and roots. These components give a biochemical foundation to many of the traditional and experimentally proven health promoting properties of okra. The available studies show that *A. esculentus* has antioxidant, anti-inflammatory, antidiabetic, antihyperlipidemic, anti-obesity, cardioprotective, hepatoprotective, nephroprotective, gastroprotective, antimicrobial, anticancer and immunomodulatory properties. The pharmacological activities seem to be connected with different molecular mechanisms, such as the activation of antioxidant defence in Nrf2-dependent way, the inhibition of NF- κ B-dependent inflammatory signalling, regulation of inflammatory cytokines, improvement of insulin signalling, modulation of AMPK and lipid metabolism, preservation of mitochondrial function, and possible regulation of gut microbiota. The poly-target effects of okra are especially important in chronic metabolic and inflammatory diseases. Although there is promising experimental evidence, there are a number of restrictions which preclude clear therapeutic

conclusions. Numerous studies use crude extracts that contain different phytochemicals, and the methods of extraction, doses used, experimental models and the design of the study make comparison with one another difficult. In addition, there are limited pharmacokinetic information and high quality human clinical evidence. Hence, at present, *A. esculentus* is not considered as a proven drug instead it may be seen as a possibility for functional food and phytopharmacology. To validate the efficacy and safety, it needs to be standardized based on phytochemical characterization, validated in terms of mechanism of action, and subjected to toxicological evaluation and bioavailability studies and then validated in adequate powered clinical trials. Incorporation of traditional knowledge with the modern pharmacological and analytical techniques can ultimately pave the way for developing scientifically validated okra-based nutraceuticals and therapeutic interventions.

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