Discover Food

Review

Exploring the nutritional, pharmacological, and industrial potential of okra and its byproducts: a comprehensive review

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Abstract
Okra (*Abelmoschus esculentus*) is a nutrient-rich and economically viable crop well known for its diverse benefits in the food and pharmaceutical industry. Besides okra fruit, its fresh leaves, flowers, and seeds are also rich in certain nutrients, including carbohydrates, protein, dietary fiber, vitamins, and minerals, significantly contributing to their beneficiary property. Moreover, okra intake provides several pharmacological benefits to the body, such as preventing chronic diseases like diabetes and hypertension due to bioactive compounds like flavonoids, polyphenols, and polysaccharides. Additionally, the diverse utilization of both okra and its byproducts in a variety of industries, such as food, textiles, pharmaceuticals, and packaging, has gained significant importance due to the use of okra pod mucilage as a natural thickening agent in food and biodegradable packaging material. Numerous health-aiding items, including protein supplements made from the fresh leaf of okra, herbal tea from the flower, and decaffeinated coffee made from the seeds, are also produced from okra and its byproducts. Further, it is easily available in sub-tropical and tropical parts of the world. Nonetheless, its potential is significantly overlooked in existing works. Owing to its potential and existing gaps, this review brings together several innovative aspects, including a detailed analysis of the nutrient profile, potential health benefits, bioactive composition, and the application of edible parts of okra. In addition, the role of okra and its byproducts in medicine, packaging, and food industries has been explored. This review also aims to highlight environmentally friendly products like biodegradable packaging and healthy products like coffee substitutes, herbal drinks, and low-calorie products from okra and its derivatives.

Keywords *Abelmoschus esculentus* · Valorization · Bioactive compounds · Fibre-rich · Health benefits · Industrial application

Abbreviations

NBH	National horticultural board
BUN	Blood urea nitrogen
BLA	Blood lactic acid
ABTS	2,2′-Azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)
DPPH	1,1-Diphenyl-2-picrylhydrazyl
MCF-7	Michigan cancer foundation-7

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HepG2	Hepatoma cells of human origin
HeLa	Human cervical cancer cells
VEGF	Vascular endothelial growth factor
MDA	Malondialdehyde
LPS	Lipopolysaccharide
TNF-α	Tumor necrosis factor
IL-6	Interleukin-6
IL-1β	Interleukin-1 beta
NF-κB	Nuclear factor kappa B
DEAE	Diethylaminoethyl
OFPS	Okra flower polysaccharide
NO	Nitric acid
COX	Cyclooxygenase
LOX	Lipoxygenase
HPMC	Hydroxypropyl methylcellulose
NaCMC	Sodium carboxymethyl cellulose
AEL	*Abelmoschus esculentus*
CMC	Carboxymethyl cellulose

1 Introduction

Okra is a member of the *Abelmoschus* species in the Malvaceae family and is also referred to as *Hibiscus esculentus* L. [1]. The fruit, their leaves, flowers and seeds are considered an excellent source of fiber, minerals, vitamins, and bioactive compounds, offering significant contribution to their beneficial properties [2]. Owing to such benefits, okra and its byproducts have established their potential in a number of industries, from food to pharmacology, due to its numerous benefits. However, hardly any literature combines a thorough use of okra and its byproducts as tablet binders, coating agents, and bio-adhesive materials in the pharmacological industries. Identifying these gaps, this review explores several innovative aspects regarding okra along with their byproducts in numerous food and medicinal applications [3]. Okra fruit has distinct names worldwide, such as *guino-gombo* in Spanish, *bhindi* in India, *lady's finger* in England, *guibeiro* in Portuguese, and *gumbo* in the United States of America [4]. Considering its nutritional composition, okra fruit includes carbohydrates, proteins, fats, vitamins, and minerals. Being a fiber rich fruit, it can be used in treatments of persistent ailments such as heart conditions, obesity, and tumour along with several other metabolic disorders such as diabetes and heart disease [5]. Moreover, okra and its extracts are used against inflammation and microbial infections, as well as as immunomodulators [6]. Indeed, numerous health advantages are linked to okra and its byproducts; for example, okra's phytochemicals have been researched for their possible medicinal results on a range of chronic conditions, including digestive, cardiovascular, and type 2 diabetes [7]. Besides, they have also been explored for their chemo-preventive, antibacterial, antifatigue, and liver detoxifying properties [8]. Also, okra mucilage is extensively used in pharmaceutical applications, including plasma replacements and blood volume expanders. Moreover, pods are advised for the treatment of dysentery, gonorrhea, and urinary problems. Furthermore, it has been stated that the seeds of this plant have fungicidal and anticancer effects, whereas immature okra pods have also demonstrated moisturizing and diuretic qualities [9]. More importantly, okra seeds are an excellent source of oil and on a small scale, it has been utilized to produce oil. Also, this can be used as a non-caffeinated coffee alternative [10]. Moreover, the bioactive compound rhamnogalacturonan in the seeds works against diabetics [11]. These leaves are a rich source of macromolecules and an excellent source of bioactive compounds [12].

Parallel studies exhibited the occurrence of lecithin in okra leaves, complexed with mucilage, that binds to carbohydrates, causing cell agglutination and glycoprotein precipitation. The bioactive compounds present in the leaves are specified to prevent breast cancer cell proliferation in vitro [9]. Similarly, the studies exhibited that concentrated flavonoid fractions from okra flowers significantly reduced colorectal cancer in vitro and in vivo while also having a potent antiproliferative effect on the growth of tumours [13]. Both the flowers and leaves are promising remedies for arthritis, allergies, and gastrointestinal inflammation [14]. This review paper examines many beneficial features of both the fruit and its byproducts, which are considerably overlooked in the existing works. Besides, the review compares the nutritional content and the beneficiary properties, which provides readers with a better understanding of the possible pharmacological benefits and applications in numerous industries.

2 Methodology

The primary goal of this comprehensive review is to explore the pharamacological and industrial benefits of okra and its by products. The data was collected and assessed from previously published works including research papers, review articles and book chapters. This review aims to identify and understand the significance and applications of okra and its derivatives. For this purpose, specific key words such as "Okraseeds", "Okra byproducts", "Nutritional composition of Okra", "Pharmacological properties", "Okra derivatives in Pharamaceuticals", "Industrial applications of Okra byproducts" were used. Relevant data for the review was gathered from all specific papers using renowned scholarly search engines such as Google Scholar, Science Direct, PubMed, Scopus and Web of Science for the manuscript preparation. The selected data archives were refined and finalised according to core idea of the study. This review does not follow a specific methodology but its main focus is on the central idea of pharmacological benefits and industrial applications of okra derivatives.

3 Nutritional profile of okra

Okra accounts for 43.4% of the world average and 73.2% of world production (National Horticultural Board [NHB] 2021-22). It is cultivated in India, Nigeria, Sudan, Pakistan, Cameroon, Ghana, and Egypt, as shown in Fig. 1. Specifically, okra covers about 485,000 hectares with a yield of 5,507,000 tons, especially productivity of about 11,354 kg per hectare in India [15]. Being a nutrient-dense fruit, okra and its byproducts offer significant nutrients like carbohydrates, fiber, minerals, vitamins, and unsaturated fatty acids such as linoleic acid, linolenic acid, oleic acids, palmitic acid, and stearic acid, all of which are vital for the human health [16, 17] as depicted in Table 1.

3.1 Okra fruit

Okra is considered a nutritious fruit, abundant in several nutrients, including micronutrients like vitamins and minerals and macronutrients like carbohydrates, fats, and proteins. Carbohydrates are the most abundant macro-nutrient in okra, mainly in viscous dietary fibers [24]. Additionally, this nutrient exhibits a major contribution to the fruit's calorific value.

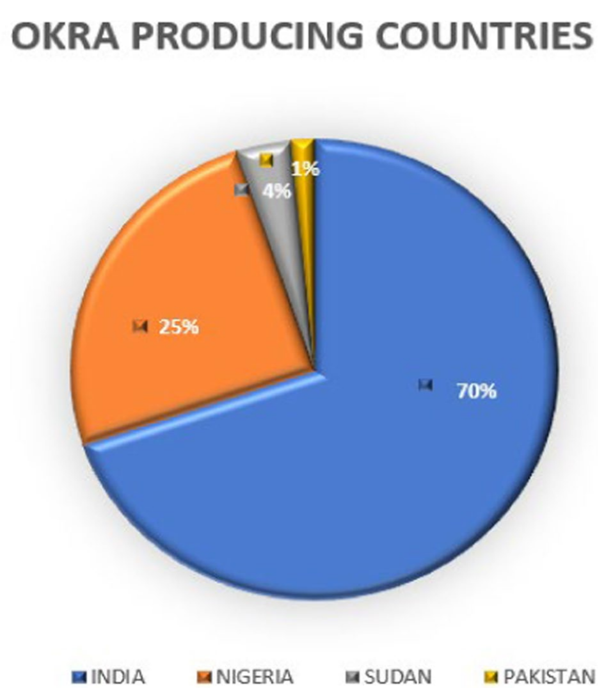

Fig. 1 The top okra-producing countries and their yield (thousand ton/year) [15]

Table 1 Nutritional profile of okra and its by-products

Components	Okra Fruit	Okra Leaves	Okra Seed	Okra flower
Proximate composition (%)				
Moisture	82.25–88.4	74.83–82.6	4.72–13.6	70–90.42
Carbohydrates	7.05–11.16	8.83–10.15	42.7–53.57	1700 KDa
Protein	2.51–2.58	4.81–6.10	21.27–23.4	NA
Ash	7.9–9.5	2.44–2.75	3.42–3.88	NA
Fat	0.18–0.46	0.19–0.93	14.40–22.62	NA
Minerals (mg/100 g)				
Potassium	103.0–303	NA	90–187.92	NA
Magnesium	53.0–57.0	NA	335	NA
Calcium	66.0–81.0	532.00	66.37–103.66	NA
Copper	0.094–0.19	0.012–0.013	< 5	NA
Phosphorus	25.62–59.72	70	16.94–1497.23	NA
Iron	0.30–0.80	0.70	< 5	NA
Manganese	0.99–1.0	0.077–0.136	< 5	NA
Vitamins				
Vitamin A (IU)	375–669	770–8387.50	NA	NA
Vitamin C (mg/100 g)	13.10–21.1	20–40	NA	NA
References	[18]	[19, 20]	[21, 22]	[23]

Likewise, the protein content in okra (2.51–2.58%) is found to be comparatively higher compared with other vegetables [25], with aspartic acid being the most abundant amino acid [26]. Even though low in fat, okra fruit is considered an abundant source of unsaturated fatty acids like linoleic acid and oleic acid [27]. In addition to being high in vitamins C and A, okra is also thought to be a rich source of vitamin B-complex, which supports a number of enzymatic processes involved in the metabolism of fatty acids, carbohydrates, and amino acids [28]. Additionally, vitamins, including ascorbic acid and folic acid present in okra, play a vital role in pregnant women by promoting fetal growth and brain development [29]. Likewise, the carotene present in okra contributes to its exceptional antioxidant properties [30]. Furthermore, okra is abundant in minerals like potassium (303 mg), sodium (8 mg), copper (0.094 mg), calcium (81 mg), magnesium (57 mg), manganese (0.99 mg), iron (0.80 mg), selenium (0.7 mg) and phosphate (63 mg) contributing to cardiovascular, skeletal, metabolic, and immune health [31].

3.2 Okra leaves

Okra leaves are considered an edible ingredient, often consumed similarly to spinach, either boiled as tea, blended into soups, or added as extracts to increase the consistency of soups, stews, and sauces [32]. These leaves are predominantly composed of carbohydrates, proteins, fibre and are also considered a rich source of magnesium, potassium, and calcium. Carbohydrates in okra leaves primarily occur in the form of mucilaginous liquid, attributed to the existence of polysaccharides (11.30/100 g) in the edible portion [25]. Moreover, the protein and fibre content available in the edible portion of the leaf is exhibited to be 4.40 and 2.10 g per 100 g, respectively. Although okra leaves are an excellent source of minerals, supplying 180 mg of magnesium, 532 mg of calcium, and 70 mg of potassium per 100 g [3, 19, 33]. Besides, researchers have reported that okra leaves contain a significant level of polyphenol antioxidants that aid in alleviating renal tubular-interstitial diseases, reducing proteinuria, eliminating oxygen-free radicals, and improving renal functions [34, 35].

3.3 Okra seeds

The composition of okra seeds varies depending on the variety and maturity phase of the okra fruit. These seeds contain notable amounts of proximate nutrients, including moisture, protein, fat, fiber, and minerals [23]. The moisture content in okra is considered significant, as it affects the engineering properties of the fruit [36]. Additionally, protein content in okra seed is observed to be exceptionally high, encompassing 28%, contributing mainly to plant-based diets. Similarly, okra seeds are analyzed as an exceptional source of fats (20–40%) [3], including linoleic acid (49.54%), oleic acid (16.81%), linolenic acid (1.48%), stearic acid (3.57%) and palmitic acid (28.60%) [17]. Besides, these seeds possess excellent amounts of crude fiber in the range of 1.94–5.96/100 g. Thus, its inclusion in the diet can be termed beneficial in several health sectors [37]. Furthermore, okra seeds are abundantly rich in various minerals like phosphorus (1450 mg), calcium (78.65 mg), magnesium (335 mg), potassium (109.76 mg), and sodium (54.78 mg), making them a valuable source of essential minerals for dietary intake [23].

3.4 Okra flowers

Okra flower, a derivative of the okra plant, is partly consumed as tea but often discarded as a waste of resources [38]. The key nutrient in okra flower is carbohydrates, major polysaccharides with a molecular mass of 1700 kDa. They also include mannose, glucose, rhamnose, galacturonic acid, and galactose, attributed to the capacity of the flowers to scavenge free radicals [34]. Moreover, hot water was used to extract polysaccharides from okra flowers, and a particular structure with a branch at C4 of 1,2,4-α-D-Rhap was identified. This structure demonstrated strong antioxidant activity, indicating their potential in nutritional food and material uses [38]. Furthermore, the moisture content in the flower is 90.42%, though the protein content is negligible, as no absorption was detected during TCA (Trichloroacetic acid) precipitation [39].

4 Bioactive components of okra and its derivatives

Okra is renowned for being an excellent repository of bioactive compounds, comprising phenolics, flavonoids, carotenoids, glutathione, glycosylated compounds, lectins, rhamnogalacturonan, and glycosides [9]. Additionally, due to the antioxidative activities of these compounds, they are indicated to be beneficial in protecting the body against oxidative stress [40] and neutralizing free radicals [41], as illustrated in Fig. 2. This section explores the different bioactive compositions present in okra and its derivatives, as depicted in Table 2, along with their related activities.

Fig. 2 Bioactive compounds in okra and its by-products

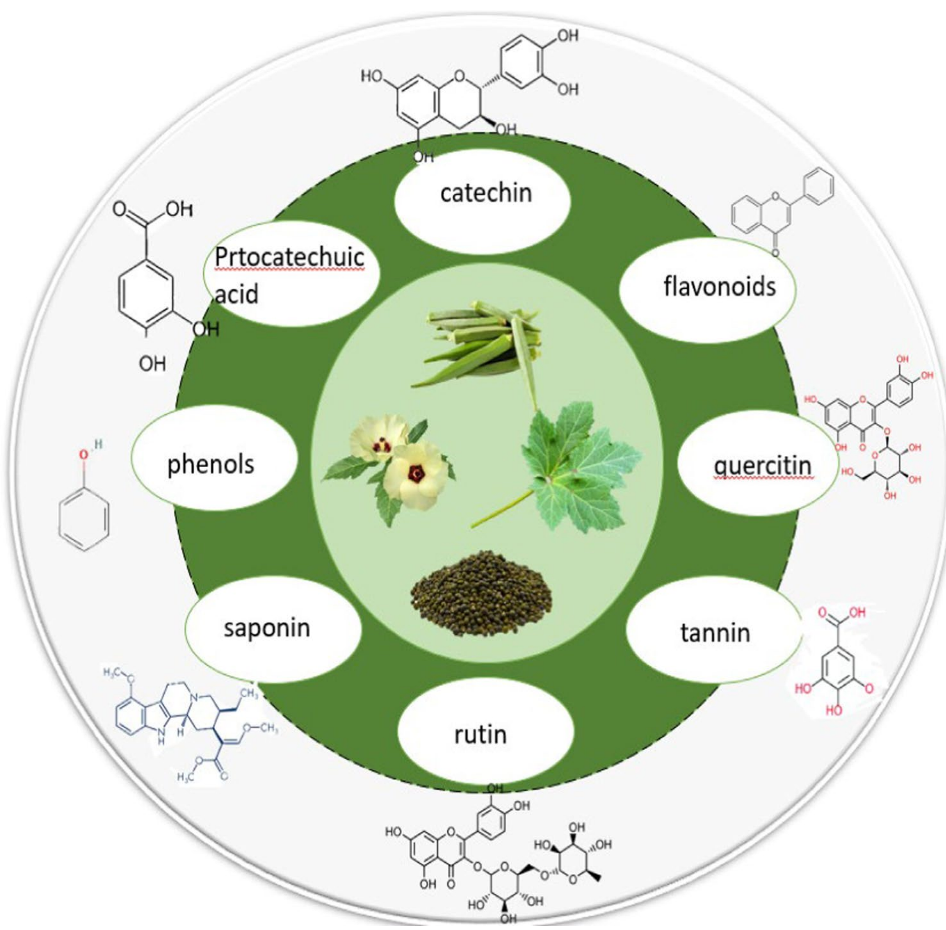

Table 2 Bioactive composition of okra and its derivatives

Bioactive components	Okra fruit	Okra seed	Okra flower	Okra leaf	References
Phenolic compounds (mg GAE/g)					
Total phenolics	18.21–25.51	2.5–2.85	40.7–44.2	4.33–7.51	[42, 43]
Protocatechuic acid	0.021–0.116	–	–	–	[44]
Catechin	–	–	0.52–0.64	–	[44]
Flavonoids (mg RE/g)					
Total flavonoids	1.88–2.95	0.07–4.54	3.28–3.42	8.36–28.27	[34, 42, 45]
Quercetin-3-O-gentiobioside	0.65–1.70	27.4–29.3	–	–	[46]
Quercetin	0.001–0.011	0.0003–0.003	–	–	[21]
Iso-quercitrin	0.38–1.07	20.64–21.11	–	–	[46]
Rutin	0.02–0.04	–	–	–	[47]
Tannin (%)					
Total tannin	0.21–0.33	0.00091–0.00378	–	0.27–3.39	[22, 48]
Polysaccharide (%)					
Total polysaccharide	7.68–20.15	5.3–14.8	15.33–20	13.0–15.2	[2, 34]
Total dietary fiber	3.5–8.2	–	–	2.14—9.12	[45]
Insoluble dietary fiber	11.9–29.9	3.20 -30.81	–	–	[45]
Soluble dietary fiber	1.36–3.43	–	–	0.4–0.92	[45]
Saponin (%)					
Total saponin	0.284–0.612	–	–	0.569–3.13	[19]

4.1 Okra Fruit

Okra fruit is composed of several bioactive compounds, including polyphenols, flavonoids, carotene, oxalic acid, and folic acid [9]. The prime phenolic substances present in this fruit include protocatechuic acid, rutin, quercetin 3-*O*-gentiobioside and quercetin-3-O-glucoside (isoquercetrin). However, the most prevalent phenolic substance present in okra is quercetin-3-O-gentiobioside, which primarily contributes to the antioxidant properties other than inhibiting the effects of digestive enzymes like lipase, α-glucosidase and α-amylase which helps in reducing the glucose absorption rate, thus controlling type-2 diabetes [49]. Additionally, flavonoids present in the form of flavanols like quercetin are specified as significant for various biological activities, such as anti-inflammatory, anti-carcinogenic, and antioxidant properties [50–52]. Further, they also contribute to the antifatigue property by lowering the amount of blood urea nitrogen (BUN) and blood lactic acid (BLA). Although the thiamine content in okra is only 0.2 mg per 100 mg, it plays a crucial role in boosting the functions of the intestine, muscles, stomach, nervous system, brain, and heart [53].

4.2 Okra leaf

The significance of okra leaves as an ingredient has been greatly increasing due to the presence of various bioactive components like carotene, thiamine, riboflavin, niacin, and amino acids at different concentrations of 385 µg, 0.25 mg, 2.80 mg, 0.20 mg and 11%, respectively, thus possessing variety of health benefits like antifungal, antidiabetic, antioxidant, anti-inflammatory and anti-hyperlipidemic properties [19, 35]. Parallel studies have exhibited the existence of lecithin in okra leaves, which forms complexes with mucilage to bind carbohydrates, causing cell agglutination and glycoprotein precipitation. Markedly, these bioactive compounds have been specified to inhibit the proliferation of breast cancer cells in vitro [9]. Moreover, the presence of tannin, particularly tannic acid (0.4%), plays a major part in imparting astringent qualities and contributing to the antinutritional traits of the leaves [19].

4.3 Okra seed

Okra seeds are an abundant source of phenolic compounds, specifically procyanidin B1 and B2, which play a role in ABTS (2,2'-azino-bis 3-ethylbenzothiazoline-6-sulfonic acid), free radical scavenging activities, and DPPH

(1,1-diphenyl-2-picrylhydrazyl) [9]. Subsequently, several studies have revealed that flavonoid constituents express enhanced cytotoxic effects on human-derived breast cancer cells (MCF-7) compared to hepatoma cells of human origin (HepG2) and human cervical cancer cells (HeLa). Similarly, in combination with other flavonoids, isoquercetin, a type of flavonoid, causes apoptosis of cancerous cells by inhibiting the vascular endothelial growth factor (VEGF) [54]. Besides, another group of flavonoids, specifically flavanols, has been identified, including catechins and certain flavanol derivatives, found at concentrations of 2.5 mg per g and 3.4 mg/100 g of seeds, respectively, showcasing significant antioxidant and anti-inflammatory properties [3]. Additionally, anti-nutritional factors like tannin and phytate are present in amounts of 0.29 and 0.91 mg/100 g, respectively [22]. Furthermore, it has been discovered that seeds have a ten-fold higher flavonoid content and a nearly 15-fold higher catechin content than the skins. Additionally, researchers have identified the presence of rhamnogalacturonan, a bioactive compound in okra seeds, associated with antidiabetic or hypoglycaemic properties [9].

4.4 Okra flower

Okra flowers have been shown to contain considerable amounts of phenols and flavonoids compared to other parts of the plant [3]. The total flavonoid content in the white and red parts of the petal was found to be 2.5 and 0.48% of fresh weight, respectively. Additionally, several flavanols, glycosides, and anthocyanins like gossypetin 3-glucosido-8-rhamnoglucoside, quercetin 4′-glycoside, cyanidin 3-glucosido-4′ glucoside, quercetin 5-glucoside, quercetin 7-glucoside, quercetin 3-diglucoside, quercetin 4′-diglucoside, quercetin 5-rhamnoglucoside, gossypetin 8-rhamnoglucoside, gossypetin 8-glucoside, cyanidin 4′-glucoside, and quercetin 3-triglucoside have been extracted from flower petals [28]. Furthermore, in red flowers, anthocyanins make up 28.5% of flavonoid content, whereas only a small fraction is present in white flowers. However, according to a new study, pure fractions of flavonoids from okra plant flowers had a strong anticancer effect on colorectal cancer in both in vivo and in vitro settings, exhibiting substantial anti-proliferative effects on tumor growth and strong antioxidant properties [13]. Activating p53 by the antiproliferative impact of flavonoids in okra flowers resulted in the disruption of mitochondrial functions in colorectal tumor cells, ultimately restraining autophagy and apoptosis [55].

5 Pharmacological importance of okra and its derivatives

Okra and its byproducts are rich sources of antioxidants such as carotene, vitamin E, flavonoids and ascorbic acid [3], making them valuable sources of nutrients and bioactive compounds, as depicted in Table 3. This nutrient density has prompted research into their pharmacological properties, revealing a variety of beneficial activities, such as antioxidant, antidiabetic, and antimicrobial activities [56] as illustrated in Fig. 3.

5.1 Okra fruit

5.1.1 Antioxidant activity

Okra exhibits exceptional antioxidant properties, chiefly due to its high polyphenol content of 29.5%. The antioxidant effect is carried out by these polyphenols, specifically from the immature okra pods, by raising the levels of glutathione peroxidase and superoxide dismutase (SOD) and decreasing those of malondialdehyde (MDA) [9]. In addition, vitamin E and carotenoids exhibit a vital role in the first line of defense against oxidative stress by quenching singlet oxygen [3]. Moreover, previous studies have highlighted the leading phenolic compounds present in okra fruits include quercetin-3-O-glucoside (isoquercitrin), quercetin-3-O-gentiobioside, protocatechuic acid, catechin derivative and rutin, a quercetin derivative, of which quercetin-3-O-gentiobioside is considered the most abundant phenolic compound [9]. Additionally, research has demonstrated that eating a phenolic compounds rich diet lowers the chance of developing neurological illnesses, cardiovascular disease, and several types of cancer [56].

5.1.2 Antidiabetic activity

Despite the low glycaemic index, numerous reports indicate that okra helps control blood sugar levels, thus preventing diabetes [9]. This outcome is attributed to the presence of the secondary metabolites in okra fruit, including triterpenoids,

Table 3 Bioactive compounds and its benefits from the okra and its derivatives

Bioactive components	Mechanism	Pharmaceutical importance	References
Phenols (Quercetin-3-O-gentiobioside, Quercetin-3-O-glucoside)	Phenols exhibit antioxidant activity by lowering the malondialdehyde (MDA) levels while increasing the superoxide dismutase (SOD) and glutathione peroxidase levels	Phenols efficiently combat certain cancers, neurodegenerative diseases, and cardiovascular diseases Quercetin plays a significant role in various cellular responses, including anti-carcinogenic, anti-inflammatory, anti-fatigue, and antioxidant properties	[56]
Flavonoids	(E)-anethole, limonene and β-caryophyllene in the okra fruit extract possess antimicrobial activity Flavonoids induce apoptosis in cancer cells, aiding cancer treatments Flavonoids inhibit the release of inflammatory cytokines and block cyclooxygenase (COX) and lipoxygenase (LOX) enzymes, which trigger inflammation	Okra possesses antibacterial and anti-fungal properties, inhibiting bacteria like *Rhodococcus opacus* and *Rhodococcus erythropolis* Flavonoids has an antiproliferative effect on MCF-7 (Michigan Cancer Foundation-7) breast and B16F10 (B16 (a mouse melanoma cell line) clone F10) skin cancer cells The Anti-inflammatory property of flavanoids make okra a promising remedy for arthritis, allergies and gastrointestinal inflammation	[13, 14, 57]
Carotenoids	Carotenoids work as the first line of defense against oxidative stress by quenching singlet oxygen	Carotenoids possess excellent anti-oxidant property which lower the risks of persistent illnesses like cancer, diabetes	[3]
Glutathione	Glutathione aids in detoxifying the liver by removing toxins and supporting liver function	The mucilage in okra contains compounds that bind bile acids and cholesterol, aiding in liver detoxification	[9]
Rhamnogalacturonan	Rhamnogalacturonan manages blood glucose levels by enhancing insulin sensitivity and slowing glucose absorption	It shows antidiabetic or hypoglycemic properties helping to regulate blood glucose levels, and prevent diabetes	[58]
Lectin	Lectin binds to specific cell surface receptors, triggering cell death pathways	This compound induces apoptosis in the cancer cells, which help in cancer treatments, help preventing breast cancer and skin cancer	[57]
Pectin	Pectin binds to bile acids, promote their excretion and stimulates bile formation, which lowers cholesterol levels	Pectin aids in reducing hyperlipidemia by reducing cholesterol and altering bile formation in the intestine	[56]
Polysaccharides	Polysaccharides enhance phagocytic capacity and inhibits proliferation of HepG-2 (Hepatocellular Carcinoma G2) cells polysaccharides inhibit the secretion of inflammatory cytokines, such as interleukin -1 beta (IL-1β), intereukin-6 (IL-6) and tumor necrosis factor (TNF-α)	Polysaccharides have immune-modulating properties, help in fighting cancer, infection and diseases Their anti-inflammatory properties work against arthritis, allergies and gastrointestinal inflammation	[14, 59]

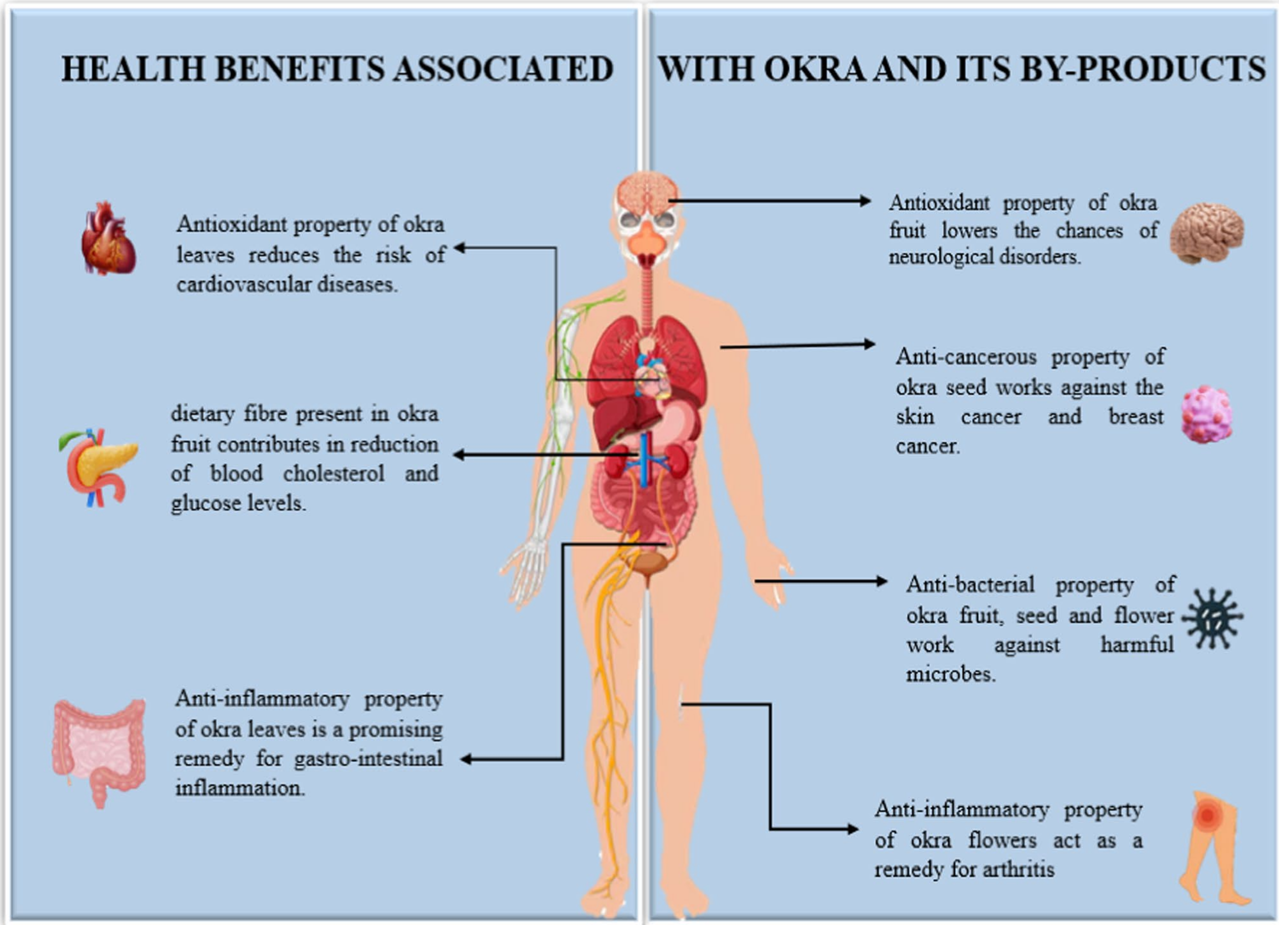

Fig. 3 Health benefits of okra and its by-products

phenolics, and the flavonoid quercetin, which functions as a hypoglycaemic agent [13]. Besides, okra's mucilage, aqueous and ethanolic extracts of the okra pods, have been proven to lower blood sugar levels [9]. Similarly, clinical trials showed that okra is exhibited to be an excellent source of pectin that aids in the reduction of hyperlipidemia by influencing the bile formation within the intestines [56]. Likewise, viscous dietary fibre also contributes to the reduction of blood cholesterol and glucose levels, as the fiber present in okra has been attributed to stabilizing blood glucose levels by regulating the rate of glucose absorption from the intestinal tract [13].

5.1.3 Antibacterial property

Okra fruit is considered an abundant source of flavonoids, polysaccharides, and other phenolic compounds. Besides, this fruit contains secondary metabolites such as saponins, cardenolides, alkaloids, and anthraquinones, which are known to possess antibacterial properties [13], thus inhibiting certain bacteria like *Pseudomonas aeruginosa, Staphylococcus aureus, Mycobacterium aurum, Rhodococcus erythropolis, Rhodococcus opacus, Escherichia coli,* and so on. Furthermore, fractions of okra pods, rich in carbohydrates, are known for their activity against *Helicobacter pylori* [9]. According to previous study findings, approximately 35 chemicals were found in the extraction of okra fruit by GC–MS analysis (Gas Chromatography-Mass Spectrometry), the most abundant of which were carvone (4.35%), decanal (4.45%), limonene (6.65%), (E)-anethole (6.7%) and β-caryophyllene (5.2%) which have been demonstrated to possess antimicrobial activity. Additionally, preliminary studies have stated that the antibacterial efficacy of okra fruit against *Escherichia coli* resulted in the best inhibition occurring at different concentrations of 40, 50, and 60%, as evidenced by the size of the inhibition zones [13].

5.2 Okra seed

5.2.1 Antioxidant activity

Okra seeds exhibit exceptional antioxidant activities due to the presence of phytochemicals such as polyphenols (29.5%), flavonoids (5.35%), isoquercitrin (2.067%), and quercetin-3-O-gentiobiose (2.741%), contributing to various therapeutic properties [61]. Moreover, these compounds help neutralize free radicals and reduce oxidative stress. In support of this, two different techniques were used to evaluate the okra seeds' total antioxidant capacity: the DPPH (2,2-diphenyl-1-picrylhydrazyl) test and the ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) test [17, 60]. Similarly, antioxidant assays, including the weight-loaded swimming endurance test, the ferric reducing antioxidant power test, and the 1-diphenyl-2-picrylhydrazyl scavenging test, exhibited that okra seeds possess significant antioxidant properties. Additionally, based on prior experiments59, the antioxidant ability of the seeds may be promoted by increasing glutathione peroxidase levels, superoxide dismutase, and reducing malondialdehyde levels [61]. Thus, incorporation of okra seeds into the diet would positively benefit the prevention of long-term illnesses such as age-related diseases and cancer [62].

5.2.2 Anti-cancer properties

Okra seeds are exhibited to be a rich source of compounds like lectins and flavonoids, owing to its ability to suppress the growth of tumor cells. A pre-clinical trial showed that lectins and flavonoids present in it are known to possess antiproliferative effect towards MCF-7 (Michigan Cancer Foundation-7) breast tumor cells and B16F10 (B16 (a mouse melanoma cell line) skin tumor cells [57]. Similarly, isoquercitrin which has higher bioavailability than quercetin, is another material that is often listed as being present in okra seeds. It also exhibits some chemoprotective properties against cancer, both in vivo and in vitro. Moreover, isoquercitrin has demonstrated suppression of colon, pancreatic, and bladder malignancies [54]. These compounds induce apoptosis in the cancer cells, which help in cancer treatments [57].

5.2.3 Antimicrobial activity

The antibacterial activity of okra seeds is primarily due to the flavonoids and oils. Okra seed extracts have been known to exhibit significant antibacterial and antifungal properties [25]. *Microsomes, lysosomes*, and the bacterial cell wall can all be harmed by the interaction of flavonoids with bacterial DNA. Previous studies have highlighted that flavonoids have lipophilic characteristics thus aid in degrading bacterial cell proteins and damaging the bacterial cell membrane [63, 64]. In addition, long-chain unsaturated fatty acids like arachidonic acid, linoleic acid, palmitoleic acid, and oleic acid are thought to be abundantly rich in okra seeds. They prevent bacteria from synthesizing fatty acids and the enzyme enoyl-carrier protein reductase, which is necessary for the creation of fatty acids by bacteria [25]. Thus, okra seeds prevent the growth of gram-negative bacteria such as *Escherichia coli and Klebsiella* [64].

5.3 Okra leaves

5.3.1 Antioxidant activity

Okra leaves are a great source of flavonoids, polyphenols, vitamin C, and vitamin A, among other antioxidants [3]. The antioxidant properties of the okra leaf extracts were determined using the 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay [34], scavenge radicals and prevent the chain initiation or break the chain propagation as the second defense line. Similarly, carotenoids and Vitamin E also support the first line of defense against oxidative stress, quenching singlet oxygen [3]. Similarly, oxygen free radicals can be eliminated with alcohol extract of okra leaves. Therefore, including okra leaves in your diet reduces the risk of chronic illnesses, including cardiac disease, cancer, and obesity, by counteracting the effects of free radicals [34].

5.3.2 Anti-inflammatory activity

Okra leaves possess excellent anti-inflammatory medication due to the presence of polysaccharides, as has been attributed to immune enhancement properties [65, 66]. According to previous studies, certain inflammatory cytokines produced (in vitro) by the NF-κB (Nuclear Factor kappa-light-chain-enhancer of activated B cells) signal pathways in response to external stimuli like lipopolysaccharide (LPS), which is enhanced during inflammation, include tumor necrosis factor (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β) [25]. Polysaccharides exert anti-inflammatory properties by blocking NF-κB signaling pathways, thus decreasing inflammation. These properties make them a promising remedy for arthritis, allergies, and gastrointestinal inflammation [14].

5.4 Okra flowers

5.4.1 Immunomodulating activity

Okra flowers are an exceptional source of water-soluble polysaccharide which are obtained by utilizing Sephacryl S-500 column and DEAE (Diethylaminoethyl)-52 cellulose for aqueous extraction and purification [56]. Results indicated that the primary components of okra flower polysaccharide (OFPS11) are galactose and rhamnose, with a molar ratio of 2.23:1 and a molecular mass of 1700 kilodalton [38]. In addition, clinical trials showed that increasing the phagocytic ability, nitric oxide (NO) secretion, and inducible nitric oxide synthase (iNOS) production, this dramatically reduced the proliferation of HepG-2 (Hepatocellular Carcinoma G2) cells [56]. Finally, the findings suggest that okra polysaccharides can be offered as a unique immunomodulators, and it is anticipated to represent a novel dietary and medicinal resource [59].

5.4.2 Antibacterial activity

The antibacterial activity of okra flowers is attributed to several bioactive compounds, like flavonoids, alkaloids and terpenoids [67]. The chemical extracted from the okra flower's ethyl acetate fraction has antimicrobial properties. Besides that, flavonoids exhibit antimicrobial activity by establishing complexes with the bacterial cell wall, inhibiting enzyme activity, and preventing microbial growth [25]. Furthermore, okra flowers inhibit the growth of four bacterial strains such as *Bacillus cereus*, *Salmonella typhi*, *Escherichia coli*, *Enterococcus faecalis*, and two fungus strains, *Candida albicans* and *Curvularia lunata* [67].

5.4.3 Anti-inflammatory activity

The anti-inflammatory properties of okra flower extracts are mainly attributed to the presence of flavonoids and polysaccharides [68]. Flavonoids are potent anti-inflammatory agents that inhibit the release of inflammatory cytokinins and blocks cyclooxygenase (COX) and lipoxygenase (LOX) enzymes which initiate inflammation [69]. Similarly, polysaccharides prevent the release of inflammatory cytokines in response to external stimuli like lipopolysaccharide (LPS), including interleukin -1 beta (IL-1β), intereukin-6 (IL-6), and tumor necrosis factor (TNF-α) [25]. These properties make them a promising remedy for arthritis, allergies, and gastrointestinal inflammation [14].

6 Utilization of okra and its derivatives in industries

In addition to its utilization for cooking, okra, and its by-products can also be used for various industrial purposes, including food, pharmaceuticals, and cosmetics, due to its valuable properties such as thickening agents, dietary fibre, and bioactive compounds [2, 41] as illustrated in Fig. 4.

6.1 Food industry

Being a crop with multiple uses, okra and its byproducts like the flower, leaf, and seed, are also processed to provide a wide range of functional products, such as seed flour, seed oil, colouring agents, okra gum, and herbal drinks (Fig. 5). Moreover, its stiffness, elastic qualities, and water-holding ability have also been utilized to create these specific products [2].

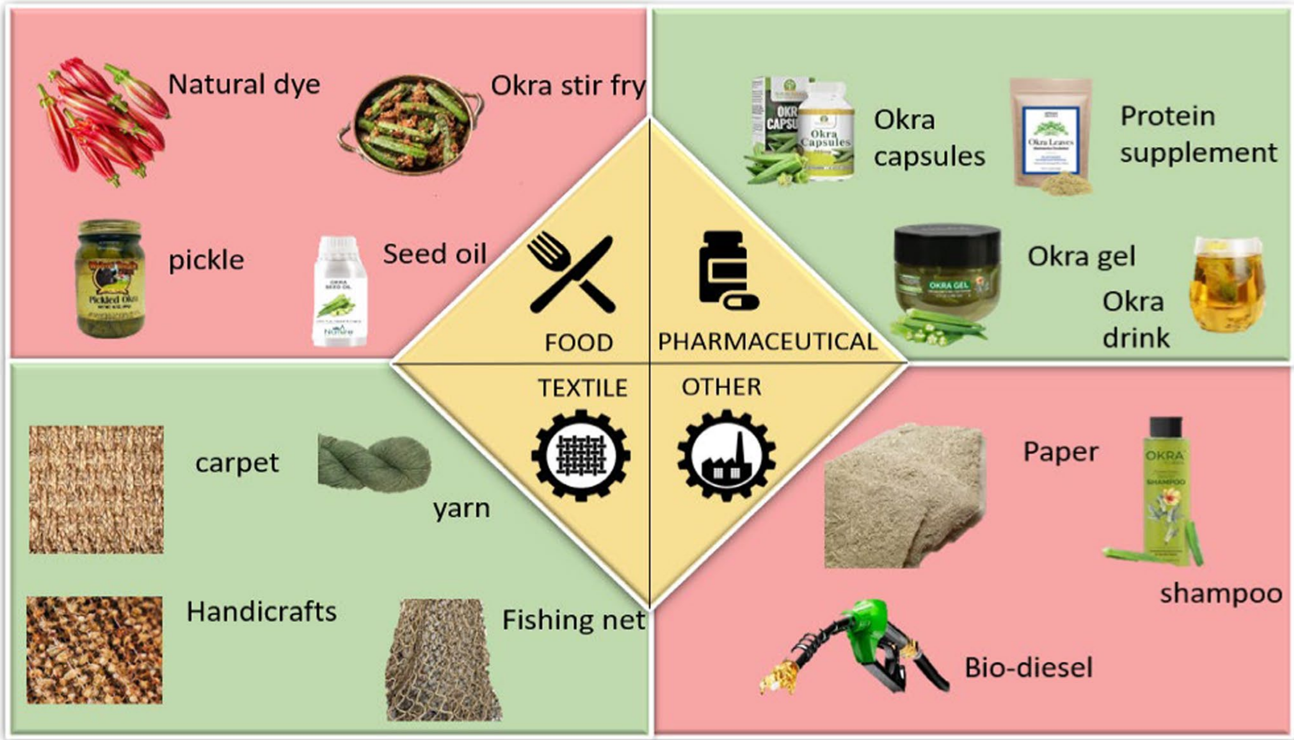

Fig. 4 Utilization of okra and its by-products in industries

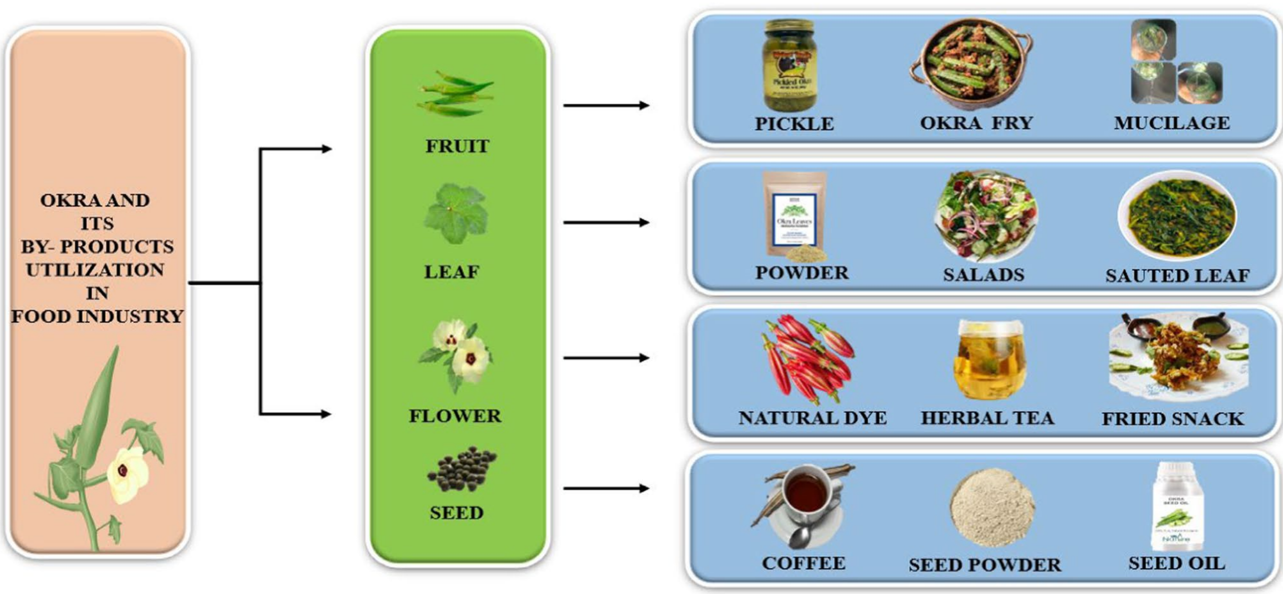

Fig. 5 Utilization of okra and its by-products in food industry

6.1.1 Okra mucilage

Emulsifiers, are the main classes of additives used in the food industry play a major role in the stability and formation of emulsions, in food products like desserts, beverages, seasonings, milk, creams, milks, and sauces [70]. Among them, lecithin, a combination of phospholipids taken from vegetable or animal sources, is one of an essential natural emulsifier used in food industry [71]. Researchers evaluated that substituting pectin derived from okra mucilage in place of lecithin in chocolate increased the yield by up to 25% compared to the formulation containing only lecithin [72]. Additionally, this substitution not only conserved the sensory characteristics of the chocolate but also increased product's nutritional worth [2].

6.1.2 Okra seed flour

Cereal-based foods serve as dietary staples for adults and are commonly used as weaning foods for infants in many developing nations. However, recent studies on the nutritional profile of okra have prompted its fortification in various products to enhance both their nutrient content and functional properties [23]. For instance, bread fortified with okra seed flour exhibited an enhancement in the protein content by 18%. Moreover, the inclusion of this flour into the breakfast or complementary food adds to the dietary intake of essential minerals, including potassium (2.14%) and sodium (0.03%) [17]. Furthermore, fortifying bread with okra seed flour offers additional health benefits due to its unique properties such as its slippery texture aids water absorption in the colon, promoting bulkier stools and improved digestion. Besides, okra seed flour also acts as a prebiotic, improving gut health, while maintaining blood sugar levels. Additionally, it binds to bile acids and cholesterol which carry toxins from the liver, facilitating their removal from the body. Also, okra's fiber guarantees a bulkier stool, which helps to prevent or alleviate constipation more effectively than crops like wheat bran, which have a rough seed coat and may irritate or damage the digestive system [73].

6.1.3 Okra seed oil

Okra seeds are recognized as a valuable source of oil and vegetable proteins, with oil content ranging from 20 to 40%. Studies have shown that okra seed oil contains 12 different fatty acids, of which 65.53% are unsaturated. These include linoleic acid (43%), oleic acid (20.16%), and 10-nonadecenoic acid (1.60%), with linoleic and oleic acids being the most prevalent. Additionally, the oil contains 34.28% saturated fatty acids, such as tetradecanoic acid, palmitic acid, heptadecanoic acid, octadecanoic acid, eicosanoic acid, docosanoic acid, and tetracosanoic acid [74]. Likewise, previous studies have proven okra seeds as a valuable source of fatty acids, including palmitic (21.9–30.4%), stearic (2.64–4.75%), oleic (16.8–27.4%), linoleic (36.5–49.5%), linolenic (0.17–2.64%), myristic (0.19–0.38%), palmitoleic (21.9–30.4%), and behenic (0.16–0.52%) acids [75] which may also aid in the treatment of spermatorrhoea. This demonstrates that okra seed can serve as an excellent source of oil, rich in natural antioxidants, and offering considerable health benefits, making it a promising candidate for development and application in various industries [74].

6.2 Pharmaceutical industry

Over 50 varieties of okra have been researched for potential use as excipients in medicinal preparations [9, 76]. Due to some existing concerns about using artificial excipients for biological tissues, natural mucilage is preferred over synthetic ones, as they are readily available, inexpensive, biocompatible, and non-toxic [77].

6.2.1 Okra gum

Gums are complex, branched polymeric structures identified for their cohesive and adhesive properties. Okra mucilage, an amorphous polysaccharide composed of L-galactouronic acid, D-galactose, and L-rhamnose exhibits various functional benefits. One of its primary applications is in the controlled and sustained release of drugs. Being non-toxic, inexpensive, readily available, and stable with less regulatory issues, okra derived gums and mucilages offer several benefits compared to synthetic pharmaceutical excipients [78]. Polysaccharides present in the mucilage of okra are used as an alternative to minimize the side effects of synthetic polymers that are frequently employed in the pharmaceutical sector [2]. Likewise, an experiment conducted [78] proved that the controlled release of paracetamol using okra gum lasted more than six hours, outperforming hydroxypropyl methylcellulose (HPMC) and sodium carboxymethyl cellulose (NaCMC), proving its effectiveness as a controlled-release agent.

Additionally, okra gum has been identified as an effective tablet binder, providing adhesive force between powder particles to form granules, which are then compressed into tablets. Studies have shown okra gum is superior to conventional binders such as povidone, gelatin, and HPMC (hydroxypropyl methylcellulose) as it reduces the tendency for fragile rupture, offers high viscous mucilage at low concentrations, and is cost-effective [78]. Moreover okra gums are effective coating agents that give long-lasting drug releasing properties or that can change the drug to have a better film coating so that the drug can survive and degrade in the stomach. Moreover, tablets coated with the gum of okra showed better physicochemical properties than the core tablets. Moreover, because of its high viscous property at lower concentrations, okra gum is a bio-adhesive material in drug delivery system [78] and aids in bonding two surfaces together [79]. Subsequently, to reduce the dosage intervals and enhance the bio availability, the drug releasing pattern of Glibenclamide was modified by forming mucoadhesive beads using sodium alignate and okra gum for drug entrapment, allowing sustained release for up to 8 h in the body [2, 78]. Furthermore, hyperglycemic levels are reported to be reduced by okra plant parts, the mucilage of okra, and ethanolic and aqueous extracts of the pods, resulting in minimizing the glucose levels in the blood of alloxan-induced diabetes models [76]. Likewise, traditional medicines use immature okra pods to reduce/prevent gastric irritations, as a diuretic agent, and to treat dental disease [28]. Similarly, skin fibroblast and human breast cancer (MCF7) were investigated using anti-tumour effect of a newly discovered lectin isolated from okra. These induce significant cell growth inhibition (63%) in MCF7 cells, and the expression of p21, caspase-9, and pro-apoptotic caspase-3, genes was increased in MCF7 cells treated with AEL, compared to those treated with control. Thereby, okra in its native form acts as a potential therapeutic to combat human breast cancer by promoting antitumor effects in human breast cancer cells.

6.3 Textile industry

In the past, natural fibers were predominantly used to meet everyday needs in various applications, including handicrafts, mats, rope, apparel, rope and carpets [4]. Today, this practice has evolved to include the extraction of valuable fibers from plant waste, such as okra, banana, pineapple, coconut, and cornhusk, promoting sustainable resource utilization [80]. Okra, with its yellow silky or light cream or white, lignocellulosic fibers similar to jute, contains 60–70% α-cellulose and holds significant potential for various textile applications in the form of fibre, yarn, and fabric such as, fibre-reinforced composites, paper laminates, twine, net, sacking, rope, decorative fabric, carpet, fishing, mats and handicraft [4]. Due to its excellent mechanical properties, including tensile strength, flexural rigidity, and frictional resistance, okra fiber is well-suited for manufacturing cloth used in packaging [81].

6.4 Packaging industry

Creation of sustainable and ecological materials encourages the search for low-cost and natural raw materials. Since biodegradable and bioactive edible films are made from natural polymeric materials including collagen, sodium alginate, and sodium carboxymethylcellulose, they offer an environmentally beneficial option for food packaging [4]. Studies have proved that edible food packaging can be made from mucilage polysaccharides and CMC (carboxymethyl cellulose) [34]. Moreover, incorporating okra fiber within the two paper sheets along with an adhesive to imparts desirable mechanical properties to paper structures as these laminates have proved to show better bond and tearing resistance compared to laminates made with pure paper sheets [4]. Likewise, natural polysaccharides are inexpensive and fully biodegradable sources of components capable of forming films. Within this aspect, on comparing films made only with corn starch, the mucilage of okra helps improve properties like water vapour barrier, strengthening biofilm structure and increasing its resistance [2]. Similarly, researchers exhibited the solubility of films in water as a significant aspect of food packaging. For instance, high sensitivity moisture foods like fish and meat require insoluble films, whereas films with high solubility are crucial for enabling easy removal of packaging through a simple wash before consumption [82].

7 Conclusion

The study highlights the potential nutritional importance, pharmacological benefits, and industrial applications of okra and its byproducts. Okra, along with its seeds, flowers, pods, and leaves, serves as an affordable and rich source of several nutrients, including protein, carbohydrates, minerals, dietary fiber, vitamins, and health-promoting fatty acids. Due to the presence of various bioactive compounds, okra possesses significant therapeutic properties such as anti-cancerous, anti-inflammatory, antidiabetic, antimicrobial, and antioxidant effects. These properties have led to its use in herbal formulations and medicines to treat a range of disorders, including ulcers, goiter, high blood pressure, chronic dysentery, diabetes, and genito-urinary issues. Furthermore, okra and its derivatives have industrial applications, such as being used as binding agents, in fiber making, paper production, and animal feed.Moreover, okra holds significant potential for advancements in agriculture, medicine, and industry. Genetic modifications could enhance its nutritional value, pest resistance, and yield. Research into okra-based drug delivery systems and bioactive compounds may lead to better treatments for diabetes and cancer. Enhancing okra gum's anti-adhesive properties could improve its efficacy in preventing bacterial biofilms in antibiotics. Currently underutilized parts like stems and flowers warrant further exploration for their nutritional and therapeutic value. Also, human trials can shed light on the health aspects of okra and its constituents, forming a scientific basis for creating awareness and popularizing okra and its components for health and wellness; therefore, continued interdisciplinary research will unlock new applications for okra and its derivatives, contributing to sustainability and health innovations.

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Data availability No datasets were generated or analysed during the current study.

Declarations

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Consent for publication Not applicable.

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