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A comprehensive review on purple corn kernels: phytochemical composition, bioactivity, bioaccessibility, health benefits, and industry applications

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ABSTRACT

Background: Purple corn (*Zea mays* L.) is a pigmented cereal crop distinguished by its high content of anthocyanins (ANCS) and other phenolic phytochemicals, which contribute to its characteristic color and biological functionality. In recent years, increasing consumer demand for natural and health-promoting food ingredients has stimulated growing scientific interest in purple corn due to its unique nutritional profile and functional properties. A comprehensive understanding of its phytochemical composition and associated bioactivities is therefore essential to support its high-value applications in functional foods, nutraceuticals, and pharmaceutical products.

Scope and approach: This review critically summarizes recent advances in the phytochemical composition and bioactive properties of purple corn, with particular emphasis on gut microbiota modulation and its effects on metabolic health, including reduced risk of developing type 2 diabetes and cardiovascular disease. In addition, emerging applications of purple corn–derived bioactive compounds in functional foods, delivery systems, and animal nutrition are highlighted, alongside current challenges and research gaps.

Key findings and conclusions: Purple corn is abundant in diverse bioactive compounds, with composition significantly influenced by cultivar, environmental conditions, maturity stage at harvest, and processing methods. Accumulating evidence from both *in vitro* and *in vivo* indicates its efficacy as a potent antioxidant, anti-inflammatory, and anticancer agent, with additional antihypertensive, anti-obesogenic, neuroprotective and immunomodulatory properties. Innovative strategies, such as nanoencapsulation, show promise in improving stability and bioavailability of bioactive compounds in purple corn, which is notably rich in anthocyanins (typically ranging from 55.8 to 1970 mg/100 g dry weight). However, toxicological evidence and clinical trials are key limiting factors for developing successful applications for purple corn as a nutritional dietary supplement or nutraceutical. Future studies should emphasize *in vivo* validation, safety assessment, and advanced delivery systems to support the development of purple corn as a functional food ingredient and potential therapeutic agent.

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1. Introduction

Corn (*Zea mays L.*), belongs to the *Poaceae* family, which was domesticated approximately 8000 years ago in Mesoamerica, with subsequent diversification in South America. Nowadays, it is ranked as the third most widely consumed cereal crop worldwide, following rice and wheat (Vilcacundo et al., 2020). Numerous varieties exist, including yellow, brown, purple and blue varieties. Among these, the ancestral k'culli-type purple corn, introduced in Europe in the late 15th century (Messer, 2000), is particularly valued for its pigmentation and rich content of bioactive compounds, making it increasingly important in the functional food and pharmaceutical industries.

Globally, purple corn is mainly cultivated in Peru, Bolivia, and parts of Mexico. As the main producer and exporter of purple corn in the world, Peru's purple corn production accounts for about 23% of the total domestic corn production (Cai et al., 2023), with a cultivation area of approximately 4000 ha and increasing demand in international markets. The grain yield of purple corn generally ranges from 3.7 to 4.4 t/ha (Melissa & Alicia, 2022), depending on genotype and environmental conditions, although productivity may vary significantly due to genotype × environment interactions (Garcia et al., 2026).

While research on corn's phytochemical components and biological activities has historically been limited, purple corn has gradually attracted considerable attention in the pharmaceutical and food industries, largely attributable to its wide spectrum of bioactive compounds, including phenolic acids, anthocyanins (ANCS), flavanols, and carotenoids (Elisa et al., 2022). Among these, ANCS and organic acids are increasingly recognized for their prebiotic potential.

Furthermore, various parts of the purple corn plant have been utilized for medicinal purposes in different traditional medicine systems. The consumption of maize bran and maize germ were evaluated as a therapeutic strategy against cardiovascular diseases (Li et al., 2024). Other findings suggest purple corn-derived bioactive exert modulatory effects on the gut microbiota, characterized by promoting the abundance of *Lactobacillus* while inhibiting pathogens such as *Shigella*, thereby contributing to intestinal barrier function (Lao et al., 2017). In recent years, products and patents related to purple corn were also on the rise: about 8 patents were filed in 2015, compared with 26 in 2025 (https://patents.google.com/).

Despite the growing number of review articles on purple corn, most of them primarily focus on photochemical composition, extraction technologies, or biological activities. Jayaprakash et al. (2023) introduced the active components of purple corn, extraction methods, and the biomedical applications of these active components. Kim et al. (2023) overviewed that purple corn pigment extracts possess various biological properties, including antioxidant, anti-inflammatory, anticancer, antidiabetic, and anti-obesity. Information on the potential of purple corn and its constituents is limited to the corn silk (Kaur et al., 2023), while comprehensive evaluations targeting how processing conditions, food matrix interactions, and gastrointestinal transformation collectively influence the bioavailability and functional efficacy of purple corn anthocyanins remains limited. Therefore, this review aims to provide a novel integrative perspective by linking phytochemical properties with bioavailability, gut microbiota modulation, and health benefits.

Specifically, this review constructs a conceptual framework that integrates processing strategies, compound stability, microbial metabolism, and physiological effects, thereby bridging the gap between compositional studies and functional applications. In addition, emerging delivery systems and industrial applications are critically discussed to highlight future opportunities for enhancing the functionality of purple corn–derived bioactive compounds, offering a more mechanism- and application-oriented perspective. A systematic literature search was conducted across Web of Science, ScienceDirect, PubMed, and Google Scholar, covering publications up to April 2025. The search strategy combined the following terms ("*Zea mays L.*" OR "purple corn"): AND (phenolic compound OR anthocyanin* OR flavonoid*) AND "biological activity" (obesity*, diabetes*, cancer*, inflammation*, etc.). Inclusion criteria were: (i) original research articles or research document (journal or book), short communication; (ii) studies investigating phenolic compounds from purple corn and their biological activities; (iii) publications in English. Exclusion criteria were: (i) studies not written in English; (ii) articles lacking experimental or mechanistic data; (iii) duplicate publications. (iv) non-accessible document. Titles and abstracts were screened initially, followed by full-text evaluation to determine eligibility. A total of 470 eligible articles was identified, and those with substantial scientific merit were incorporated into the discussion.

2. Nutritional profiles of purple corn kernel

Purple maize contains 61% - 78% starch, 10% non-starch polysaccharides, 6% - 12% proteins, 3% - 6% lipids, as well as various minerals and vitamins (Jayaprakash et al., 2023). The chemical compositions of purple corn are summarized in Table 1 and representative chemical structures are shown in Fig. 1. Copper, manganese, iron, zinc, magnesium, calcium, phosphorus, potassium are minerals distributed in the purple corn. Lee et al. (2021) analyzed the phytochemical composition of purple corn from Malaysia and identified 130 compounds, mainly phytochemicals such as phenolics, flavonoids, alkaloids, esters, fatty acids, and others. Jiang et al. (2023) analyzed the metabolites in red-purple and purple-black maize varieties. A total of 524 metabolites were identified, with the majority comprising flavonoids (19.66%), amino acids and their derivatives (16.03%), phenolic acids (14.12%), lipids (11.07%), alkaloids (9.54%), nucleotides and their derivatives (8.40%), organic acids (5.15%), and lignans and coumarins (2.10%). Total bound phenolic content detected in nine Bolivian purple corn varieties ranged from 242.9 to 529.6 mg gallic acid equivalent/100g dry basis (db). In conclusion, literature related to the chemical composition of purple corn mainly focuses on the impact of growing region, species, cultivar, processing methods, growth stages, and extraction methods.

2.1. Carbohydrate

The carbohydrates in purple corn kernels include monosaccharide (D-mannose, D-fructose, D-glucose, D-(−)-fructose), disaccharides (D-cellobiose, sucrose), polyols (D-sorbitol) and starch (Feng et al., 2024a). Significant differences in carbohydrate composition were observed between purple (black/purple) and yellow maize varieties. The available carbohydrate content (AVC) ranged from 61.09 to 79.98 g/100 g across all samples. Notably, the purple maize sample (Manipuri black) exhibited a relatively high AVC (79.14 g/100 g), whereas the yellow maize varieties (Janjheli-5 and Janjheli-6) showed the lowest values (61.09–61.36 g/100 g) (Gogoi et al., 2023). In addition, after the application of nitrogen fertilizer, the soluble sugar content in purple waxy maize grains decreased, while the content of amylopectin content increased from 36.27% to 66.62% (Feng et al., 2024a).

2.2. Amino acid and protein

Purple corn kernels were harvested between 15 and 31 days after silking. Phenylalanine and tyrosine, two precursors of ANCS, ranked second and third lowest in mass, respectively (Kim et al., 2020). Therefore, evaluating the amino acid content and anthocyanin accumulation patterns during the grain filling stage helps in harvesting corn kernels with high nutritional value. Compared with conventional yellow dent corn, purple flint maize exhibits slightly lower total protein content (e.g., yellow dent: 3.4% vs purple flint: 3.0%). This compositional difference may influence digestibility, functional properties, and nutritional value (Ildiz et al., 2019). Except for the common amino acids, L-cysteine, citrulline, cystine, 4-aminobutyric acid (GABA) were detected in purple corn (Jiang et al., 2023). The germination process and

Table 1
Chemical compositions of purple corn kernel.

Group	Chemicals	Major differences with normal corn	References
Carbohydrates	D-Glucose, D-mannose, D-fructose, D-(−)-fructose, D-(+)-cellobiose, sucrose, D-sorbitol, rhanmnose, galactose, starch	Similar carbohydrate profile to normal corn (~70–75% DW)	Feng et al. (2024a)
Phytosterols and Esters	4-demethylsterols, sitosterols, 4,4-dimethyl-sterols, 4-monomethylsterols, stigmasterol, delta5-avenasterolare, cyclandelate	Comparable levels (~70–120 mg/100 g oil)	Lee et al. (2021)
Amino acids and Proteins	4-aminobutanoic acid (GABA), 20 common amino acids and derivatives, zein proteins, glutelin proteins, globulins proteins, albumins proteins, globulins proteins	Protein content similar (~8–11% DW), dominated by zein	Feng et al. (2024b)
Organic acids	Monobasic acids (C8-C24), C18.1N9C, C18.1N9T, C18.2N6C, C18.2N6T, C18.3N3, C18.3N6, C20.3N3, C20.3N6, C20.4N6, C20.5N3, C22.1N9, C22.6N3, stearic acid, docosahexaenoic acid, glycocholic acid, malonic acid, fumaric acid, quinic acid, palmitic acid, arachidic acid, myristic acid, oleic acid, phytic acid, 2-butenedioic acid, succinic acid, aconitic acid	Similar fatty acid profile; linoleic acid ~50–60% in both	Lee et al. (2021)
Alkaloids	sinomenine, codeine	Present in trace amounts; limited reports in normal corn	Lee et al. (2021)
Phenolic compounds	6-Gingerol, 4-methylumbelliferone	~3–10× higher than normal corn (~100–300 mg GAE/100 g DW)	Lee et al. (2021)
Phenolic acids	benzoic acids (protocatechuic acid, *p*-hydroxybenzoic acid, 2,4,6-trihydroxybenzoic acid and vanillic acid), cinnamic acids (caffeic acid, 3-O- caffeoylquinic acid, *p*-coumaric acid, 3-O-Feruloylquinic acid and ferulic acid), chlorogenic acid, syringic acid, *p*-hydroxyphenyl acetic acid	Ferulic acid dominant; total phenolic acids ~2–5× higher	Xia et al. (2024)
Anthocyanin flavonoids	Cyanidin (cyanidin-3,5-O-diglucoside, cyanidin-3-O-xyloside, cyanidin-3-O-rutinoside, cyanidin-3-O-(6-O-p-coumaroyl)-glucoside, cyanidin-3-O-sophoroside, cyanidin-3-O-glucoside, cyanidin-3-O-galactoside, cyanidin-3-O-arabinoside, cyanidin-3-O-(6-O-malonyl-beta-D-glucoside)), delphinidin (delphinidin-3-O-glucoside, delphinidin-3-O-rutinoside, delphinidin-3-O-rutinoside-5-O-glucoside), malvidin (malvidin-3-O-5-O-(6-O-coumaroyl)-diglucoside, malvidin-3-O-glucoside), pelargonidin (pelargonidin-3-O-arabinoside, pelargonidin-3-O-rutinoside, pelargonidin-3-O-glucoside, pelargonidin-3-O-5-O-(6-O-coumaroyl)-diglucoside, pelargonidin-3-O-(6-O-malonyl-beta-D-glucoside), pelargonidin-3-O-(6-O-p-coumaroyl)-glucoside, pelargonidin-3-O-sophoroside, pelargonidin-3,5-O-diglucoside), peonidin (peonidin-3-O-(6-O-malonyl-beta-D-glucoside), peonidin-3-O-(6-O-p-coumaroyl)-glucoside, peonidin-3,5-O-diglucoside, peonidin-3-O-arabinoside, peonidin-3-O-glucoside, peonidin-3-O-rutinoside, petunidin-3-O-rutinoside, petunidin-3-O-glucoside, petunidin-3-O-(6-O-p-coumaroyl)-glucoside, petunidin-3-O-(6-O-malonyl-beta-D-glucoside)), procyanidin B3	Absent in normal corn	Xia et al. (2024)
Nonanthocyanin flavonoids	Epicatechin, epigallocatechin, (+)-catechin, epigallocatechin gallate, myricetin, hirsutrin, morin, rutin, hesperitin, luteolin, vitexin, hyperoside, naringenin and its glycosides (naringenin-7-O-glucoside), apigenin and its glycosides (apigenin-6,8-di-glucopyranoside), quercetin and its glycosides (quercetin-3-O-rutinoside, quercetin-3-O-glucoside, quercetin-4′-O-glucoside, quercetin-3-(6″-malonyl)-glucoside), kaempferol and its glycosides (kaempferol-3-O-hexoside), catechin, vanillin, prunin, 6″-O-Malonylisoquercitrin, Isorhamnetin, 3′,4′,5,7-Tetrahydroxyflavanone, 7,2′,3′-Trimethoxyflavone, Isorhamnetin-3-O-rutinoside and 5,3′-Dihydroxy-6,7,4′-trimethoxyflavone	Higher diversity and content than normal corn	(Ali et al., 2024; Kumar et al., 2024; Lee et al., 2021)
Aroma compounds	hexanal, 1-octen-3-ol, 1-hexanol, (E)-2-nonenal, 1-heptanol, 2-methyl-2-butenal, (Z)-3-nonen-1-ol, 3-ethyl-2-methyl-1,3-hexadiene, 2,3-butanediol, 2,4-bis(1,1-dimethylethyl)-phenol, 1-hydroxy-2-propanone, 3-hydroxy-2-	Similar volatile profile with minor differences	Buttery et al. (1997)

(*continued on next page*)

Table 1 (*continued*)

Group	Chemicals	Major differences with normal corn	References
	butanone, 2-heptanone, acetaldehyde		
Carotenoids	Xanthophylls (Lutein, 13-cis-lutein, 13′-cis-lutein, All-trans-zeaxanthin, Zeinoxanthin, Zeaxanthin), Carotenes (β-Carotene, α-Carotene, 13-cis-β-carotene, All-trans-β-carotene, 9-cis-β-carotene), Cryptoxanthins (β-Cryptoxanthin, 13-cis-β-cryptoxanthin, All-trans-β-cryptoxanthin)	Lower (~1–5 mg/kg) vs yellow corn (~15–25 mg/kg) due to anthocyanin dominance	(Camargo et al., 2024)

stress factors, such as lower temperatures and higher ultraviolet (UV) radiation, commonly associated with regions at higher altitudes, may promote the accumulation of GABA in maize kernels (Galvez Ranilla et al., 2021). Compared to the corn flour percentage (8.53%) from ungerminated corn seeds, germination of purple corn seeds at different temperatures (15 - 40 °C) for different durations (72, 120, 168 h) increased the protein content in the kernels. In addition, extraction conditions, varieties, and maturity can all influence the protein content (Saikaew et al., 2018). The proteins in purple corn also include enzymes related to the carbon and nitrogen cycles, the application of an appropriate external nitrogen input promotes nitrogen metabolism and carbohydrate biosynthesis in purple corn kernels (Feng et al., 2024a).

2.3. Phytosterols

The predominant phytosterol identified in maize is sitosterol, accounting for approximately 77% - 87% of the total phytosterols extracted from maize. However, reports on phytosterols in purple corns are scarce. Most plants oils contain approximately 1–5 g/kg of phytosterols, whereas corn oil exhibits significantly higher levels (5.13–9.79 g/kg), highlighting its potential as a valuable dietary source of phytosterols (Siyuan et al., 2018). Rodríguez-Miranda et al. (2022) detected phytosterols in various parts of purple corn, including grains, leaves, and cobs, indicating that these compounds are broadly distributed throughout the plant.

2.4. Organic acids

Organic acids in purple corn include intermediates of the tricarboxylic acid (TCA) cycle and other bioactive acids. Highland purple corn exhibits higher levels of TCA cycle intermediates, such as fumaric and succinic acids, compared with lowland varieties (Galvez Ranilla et al., 2021). Metabolomic analyses based on ^{1}H NMR have demonstrated that Zamorano yellow maize grown under agroecological management showed elevated levels of several organic acids, including 2-hydroxybutyrate, citrate, succinate, and fumarate, which are key intermediates of the TCA cycle (Medina-Mendoza et al., 2026). These findings underscore the role of agroecological management in improving maize nutritional quality, while promoting more sustainable agricultural production.

2.5. Alkaloids

Alkaloids are rarely reported in purple corn. Lee et al. (2021) identified two alkaloid compounds in Malaysian purple corn, namely sinomenine and codeine. These two alkaloid compounds possess a range of bioactivities, including anti-inflammatory, antimicrobial, and antioxidant effects (Jabbar et al., 2024).

2.6. Phenolic compounds

The diverse TPC is due to the different standard, purple corn variety, and extraction methods used. It is also important to note that phenolic compounds in purple corn are unevenly distributed within the kernel, with the majority—particularly anthocyanins—being predominantly localized in the pericarp (Li et al., 2017), as supported by histological evidence showing strong pigment accumulation in this outer layer (Kumar et al., 2024). The main classes of phenolic compounds present in purple corn are phenolic acids, ANCS and non-anthocyanin flavonoids.

2.6.1. Phenolic acids

Phenolic acids identified in purple corn include benzoic acid, ferulic acid, *p*-coumaric acid, protocatechuic acid, vanillic acid, syringic acid, caffeic acid, chlorogenic acid, *p*-hydroxyphenyl acetic acid. Zhang et al. (2019a) determined the phenolic acid content in 20 different varieties of Apache purple maize. Overall, ferulic acid (186.2 - 2530.8 μg/g dw) predominated the phenolic composition in purple maize powder extracts, followed by protocatechuic acid (80.7 - 1159.5 μg/g dw) and vanillic acid (0 - 1168.7 μg/g dw). A study on Bolivian maize reported a higher ferulic acid concentration in purple maize (298.4 mg/100 g dw) compared to yellow maize (132.9 mg/100 g dw) (Cuevas Montilla et al., 2011). Extraction methods significantly influence phenolic acid yield and profile. Compared with microwave-assisted extraction (42.4% v/v ethanol, 75 °C, 29 min), ultrasound-assisted extraction (50% v/v ethanol, 21 min, 28 °C, 50% ultrasonic amplitude) from purple corn pericarp powder yielded higher individual phenolic acid profile, particularly chlorogenic acid, caffeic acid and ferulic acid (Boateng et al., 2023).

2.6.2. Anthocyanins

ANCS are water-soluble polyphenolic compounds responsible for imparting a spectrum of colors, ranging from dark purple-red to purple, in corn (Lao et al., 2017). Notably, purple corn contained 4910 mg ANCS/kg db, which was markedly higher than the level observed in blue corn (363 mg ANCS/kg db) (Boateng et al., 2023), highlighting its strong potential as a rich anthocyanin source for functional food and nutraceutical applications. The anthocyanin profile of purple corn is mainly composed of both non-acylated and acylated derivatives. Structurally, these compounds are predominantly modified through glycosylation (primarily with glucose) and subsequent acylation, with malonyl groups being the most common acyl substituents. In addition, acylated anthocyanins are often conjugated with phenolic acids or related compounds, contributing to enhanced molecular stability and color intensity (Zhang et al., 2019a). Furthermore, a total of 39 anthocyanin derivatives (monomeric forms) has been identified in purple waxy corn cultivars, which can be classified into eight distinct anthocyanin classes, as summarized in Table 1.

2.6.3. Other flavonoids

In addition to phenolic acids and ANCS, various other flavonoids are also widely found in purple corns kernels, including flavones, flavanols, isoflavones, flavanones and flavonoid glycosides. Epicatechin has been reported as the most abundant flavonoid in multiple purple corn varieties, with concentrations up to 759.7 μg/mL in pericarp from Andean cultivars (Ali et al., 2024a). 13 different flavonoids compounds were identified, such as prunin, quercetin-4-O-glucoside, quercetin-3-(6″-malonyl)-glucoside, 6″-O-malonylisoquercitrin, isorhamnetin, apigenin-6,8-di-glucopyranoside, vitexin, 3′,4′,5,7-tetrahydroxyflavanone, naringenin, hyperoside, 7,2′,3′-trimethoxyflavone, isorhamnetin-3-O-rutinoside and 5,3′-dihydroxy-6,7,4′-trimethoxyflavone (Ali et al., 2024a). Kumar et al. (2024) also found that epicatechin was the most abundant flavonoid identified in most of the evaluated 14 varieties purple corn, with the “Bloody butcher” and “Apache purple” varieties having higher concentrations of quercetin. Overall, the composition and contents of flavonoids in purple corn are

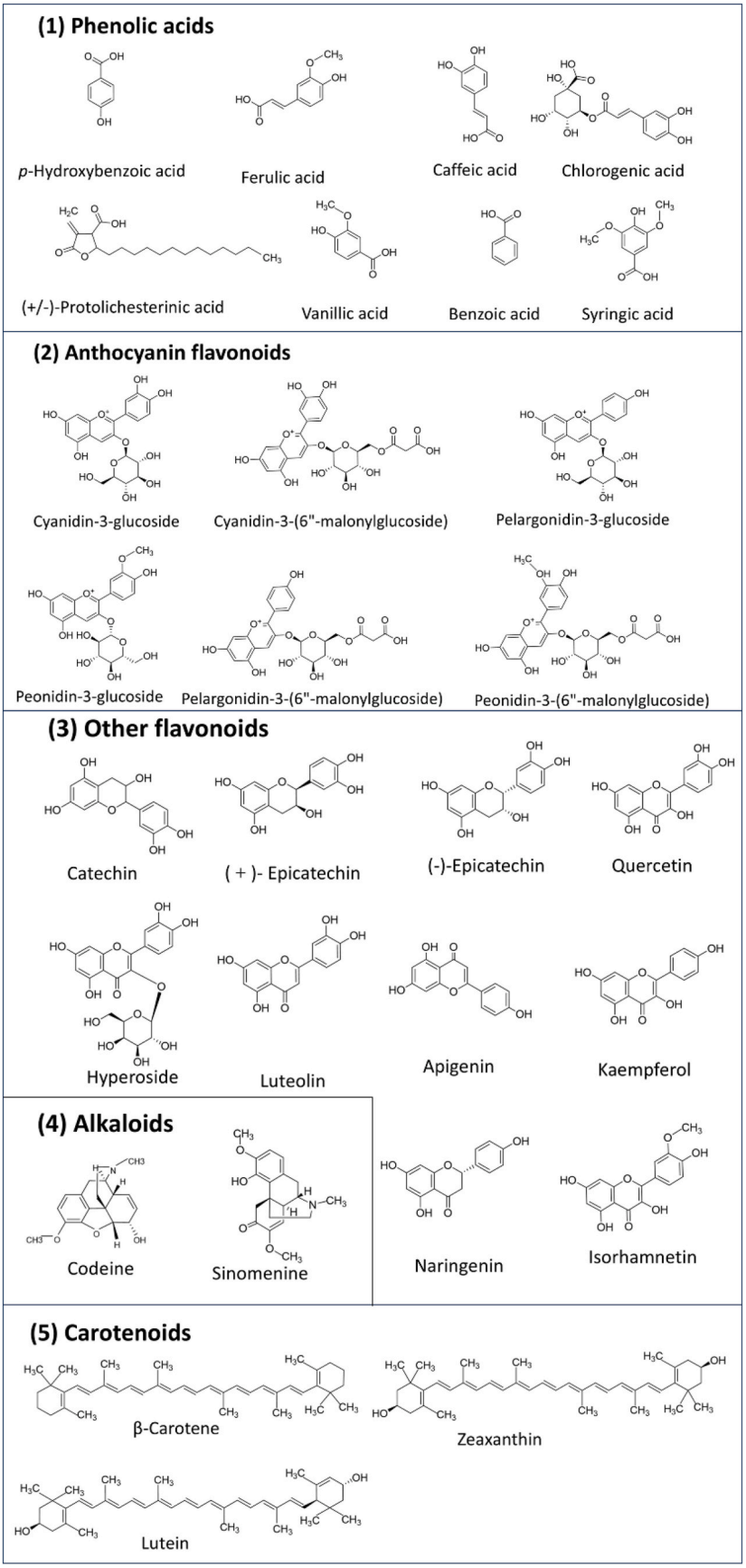

Fig. 1. Chemical structure of purple corn kernels.

influenced by different factors, including variety, extraction method, and geographical origin.

2.7. Aroma compounds

Aroma compounds in purple sweet corn juice were reported by Feng et al. (2020). Fifty-four compounds, such as 1-pentanol, 2-propanamine, 3,3′-Iminobispropylamine and 5-methyl-2-phenylindolizine, were identified exclusively from the raw corn juice. After boiling, 49 compounds were identified, including 2,3-octanedione, (Z)-2-heptenal, 3-nonenoic acid, tetradecanoic acid and 2,4-bis(1,1-dimethylethyl)-phenol. These findings indicate that thermal processing modifies the aroma profile, potentially affecting flavor perception.

2.8. Carotenoids

Another reason for which purple corn strongly attracted widespread attention is its carotenoid composition, which not only provides its pigmentation but also contributes significantly to its health benefits. The xanthophylls compounds detected in purple corn also include lutein, zeaxanthin, 13-cis-lutein, 13′-cis-lutein, All-trans-zeaxanthin, and zeinoxanthin (Camargo et al., 2024a). Compared with the yellow (67.5 ± 0.6 μg g^{-1}) and red (35.8 ± 0.8 μg g^{-1}) maize, blue and purple maize contain considerably lower qualities of total carotenoids, at 1.1 ± 0.1 μg g^{-1} and 0.4 ± 0.3 μg g^{-1}, respectively. These findings further reinforce the hypothesis that the elevated anthocyanin content is responsible for the purple coloration in maize, while the higher carotenoid content accounts for the yellow hue.

3. Bioavailability and bioaccessibility of purple corn kernels

As mentioned above, the health benefits of purple corn kernels have been widely recognized, with the main bioactive components, such as ANCS and carotenoids - contributing to its anti-oxidative, anti-inflammation and anti-cancer properties. However, studies have shown that, due to these bioactive compounds large molecular size, molecular weight, high polarity and instability, the beneficial effects during ANCS -enriched foods consumption may be significantly reduced (Victoria-Campos et al., 2022). In addition, ANCS, which are the major polyphenols in purple corn, are highly sensitive to environmental conditions such as light exposure, temperature, metal ions, enzymes and antioxidants, all of which can further promote their degradation or transformation during digestion and processing (Zhang et al., 2026).

Under *in vivo* conditions, factors such as pH, other substrate matrices, digestive enzymes, and the activity of gut microbiota can exacerbate the structural changes of ANCS, thereby affecting their bioavailability in the gastrointestinal tract (Victoria-Campos et al., 2022). Thanks to the metabolomic approach, it is now understood that the bioavailability of ANCS is not as low as previously thought (less than 1-2%) (Giampieri et al., 2023), although the value is slightly higher, a low recovery is still considered.

3.1. Factors affecting the bioavailability of purple corn

3.1.1. Chemical structures and its related properties affecting bioavailability

Their chemical stability, solubility, and molecular structure of ANCS are key properties that influence their bioaccessibility. During the oral phase, a decrease in the content of the three cyanins derivatives, cyanidin-3-(6′malonylglucoside) (C-3-(6″MalGlu)), C3G and cyanidin-3-(3″,6″, dimalonylglucoside) - (C-3-(3″,6″, diMalGlu)) was observed. In contrast, during the gastric digestion phase, C-3-(6″MalGlu) showed an increase tendence, reaching a concentration of 436.6 μg/g dw and a preservation of 90% compared with the undigested samples (Rodriguez et al., 2024). At the end of digestion, C-3-(6″MalGlu) remained the predominant compound, followed by C3G and C-3-(3″,6″-diMalGlu), with residual levels of 27%, 17%, and 24%, respectively (Rodriguez et al., 2024). Ferron et al. (2020) observed a similar trend in an *in vitro* digestion experiment of a new Italian maize variety. After the gastric phase, the relative abundance of C3G and P3G was higher than expected, followed by a sharp decrease at the end of the intestinal phase. This behavior can be attributed to the relatively high stability of anthocyanins under acidic gastric conditions, where they predominantly exist in the flavylium cation form (Prayoga et al., 2025).

3.1.2. Purple corn bioaccessibility influenced by physical treatments and environmental factors

The acidic steeping process (pH = 2) can significantly increase the bioaccessibility of C3G in freeze-dried purple maize (native vs. acidic process control: $P < 0.0001$) (Fiecke et al., 2024). This effect is likely attributable to the greater stability of ANCS in low-pH environments (Prayoga et al., 2025). Additionally, light plays a crucial role in regulating the accumulation of ANCS, as it plays a fundamental role in gene activation that affects the biosynthesis of ANCS in maize plant tissues and cells (Duangpapeng et al., 2024). Moreover, processing conditions may affect the bioavailability of phenolic compounds. In baked purple corn systems, a pronounced decrease in anthocyanin content has been reported under high-temperature conditions (175 °C for 6 min), reflecting the inherent thermal instability of anthocyanins. Such degradation is mainly driven by hydrolysis and deglycosylation reactions, followed by ring-opening processes that generate chalcone structures and their isomers, which may further convert into α-diketones and ultimately degrade into low-molecular-weight phenolic acids and aldehydes (Feng et al., 2025). Méndez Lagunas et al. (2022) compared tortillas prepared by traditional nixtamalization using $Ca(OH)_2$ with those produced by ecological nixtamalization (EN) employing alternative calcium salts ($CaCl_2$, $CaCO_3$, and $CaSO_4$). Their results indicate that EN process with $CaCl_2$ achieved the highest bioaccessibility of TPC. Specifically, relative TPC bioaccessibility ranged from 390% to 520% in *tlayuda* and from 487% to 666% in soft tortillas. These results suggest that EN may better preserve or enhance phenolic compounds in corn products, offering a more favorable balance between nutritional quality and sustainability compared with traditional methods (Méndez Lagunas et al., 2022).

3.1.3. Interactions between purple corn and additional food matrix

Camargo et al. (2024c) conducted an *in vitro* digestion experiments to study the bioaccessibility of carotenoids in purple and yellow corn extrudates co-consumed with different types of milk (semi-skimmed, skimmed, and whole). Lipid content in milk did not exert a significant effect on carotenoids bioaccessibility in purple corn products (Camargo et al., 2024c). However, dietary fiber content, which is approximately five times higher in purple corn compared with yellow corn, may contribute to lower carotenoid bioaccessibility, highlighting the importance of matrix composition in determining nutrient availability (Camargo et al., 2024c).

3.2. Strategies for bioavailability and bioactivity enhancement of bioactive compounds in purple corn

3.2.1. Encapsulation

The instability of ANCS, particularly under varying pH, temperature, and oxygen conditions, significantly limits their bioavailability and practical applications. (Deng et al., 2023). Encapsulation has emerged as an effective strategy to overcome these limitations by physically protecting anthocyanins from environmental degradation and enabling controlled release during gastrointestinal digestion (Guo et al., 2018). Alginate-pectin hydrogels enhance anthocyanin stability by forming a protective three-dimensional matrix that limits environmental exposure, maintains an acidic microenvironment, and stabilizes anthocyanin structures through molecular interactions, thereby significantly reducing degradation. (Guo et al., 2018). Similarly, pectin-based

nanoparticles, improve thermal and storage stability by electrostatic interactions and protein–polyphenol binding, which help preserve anthocyanin structure (Rosales et al., 2023). Importantly, *in vitro* digestion studies demonstrate that such systems can protect anthocyanins during gastric digestion while enabling their gradual release in the intestine, thereby improving bioaccessibility (Rosales et al., 2023).

3.2.2. Co-pigments

Co-pigments are colorless or lightly colored molecules that form non-covalent complexes with anthocyanins, enhancing their color intensity and stability through intermolecular interactions such as π–π stacking, hydrogen bonding, and charge-transfer mechanisms (Gençdağ et al., 2022). Pang et al. (2024) reported that polysaccharides, organic acids, and colloids can act as effective co-pigments. Specifically, fructose (15%), tannic acid (0.06%), and pectin (2.0%) significantly inhibited thermal degradation of anthocyanins in purple corn. This stabilizing effect is mainly attributed to the formation of protective molecular complexes, which reduce the susceptibility of anthocyanins to heat and oxidative stress.

3.2.3. Enzymatic treatment

Enzymatic modification, particularly acylation, has recently attracted considerable attention from the scientific community due to its significant ability to enhance the stability and bioactivity of ANCS by increasing molecular hydrophobicity and steric hindrance. For instance, treatment with Candida antarctica lipase B in the presence of octanoic acid significantly increased the half-life of total anthocyanins at 80 °C from 6.05 to 10.05 h ($p < 0.05$), which is attributed to enhanced structural rigidity and reduced susceptibility to nucleophilic attack (Yañez Apam et al., 2023).

4. Effects of purple corn kernels on intestinal microbiota and related mechanisms

The gut microbiome, a critical determinant of host health, has its composition influenced by environmental and lifestyle factors, and its dysregulation is associated with a variety of diseases and health conditions, including gastrointestinal disorders, metabolic-related diseases, and neuropsychiatric disorders, among others (Wu et al., 2019).

In recent years, increasing attention has been paid to plant-derived natural products as promising modulators of gut microbiota composition and activity. Purple corn, a rich source of polyphenolic compounds, particularly ANCS, has emerged as a promising dietary modulator of the gut microbiome, enhance the production of short-chain fatty acids (SCFAs), and promote the enrichment of beneficial bacteria such as *Lactobacillus* (Xu et al., 2021). Additionally, individual monomeric compounds have demonstrated regulatory effects on the gut microbiota composition. Li et al. (2025) found that peonidin-3-O-(3,6-O-dimalonyl-β-D-glucoside) (P3GdM), isolated from black corn cobs, enhances the production of SCFAs and lactic acid by modulating gut microbiota composition, suppresses intestinal inflammation which contributes to improved intestinal barrier functions. Mechanistically, the modulation of gut microbiota by purple corn ANCS is closely linked to host metabolic and immune pathways. ANCS from purple corn have been found to increase the abundance of lactic acid bacteria in the gut of high-fat diet-induced obese mice and decrease the prevalence of *Helicobacter* pylori, promoting mitochondrial metabolism through the AMPK signaling pathway and thereby inhibiting hepatic lipid accumulation (Xu et al., 2021). Moreover, purple corn extract has demonstrated anti-inflammatory effects by regulating microbiota composition, which contributes to reduced macrophage infiltration and alleviation of neuropathic pain (Magni et al., 2019). Clinical evidence further supports these findings. In patients with inflammatory bowel disease (IBD), supplementation with purple corn extract rich in ANCS significantly reduced pro-inflammatory bacteria (e.g., *Alistipes* and *Erysipelotrichaceae UCG-003)* and increased beneficial taxa such as *Parabacteroides*, leading to improvements in lipid metabolism and intestinal inflammation (Vacca et al., 2024). Similarly, ANCS intake as an adjuvant therapy has been shown to enhance intestinal barrier function and reduce relapse risk in IBD patients (Liso et al., 2022).

In summary, these findings suggest that purple corn extract, rich in ANCS, exerts beneficial effects primarily through modulation of gut microbiota composition and function. This modulation is associated with increased production of SCFAs, enrichment of beneficial microbial taxa, and maintenance of gut microbial homeostasis. Consequently, these changes contribute to enhanced intestinal barrier integrity, reduced systemic inflammation, and improved metabolic regulation, thereby potentially lowering the risk of obesity and inflammation-related diseases, such as colorectal cancer. The overall impact of gut microbiota modulation on host health is illustrated in Fig. 2.

5. Health implications of purple corn kernels

Purple corn is gaining considerable attention in the market for innovative ingredients, rich in phenolic compounds, that may offer health benefits. Extracts and individual components from purple corn kernels have been shown to demonstrate a wide range of biological activities, both *in vitro* and *in vivo* models. These health benefits of purple corn kernels are summarized in Fig. 3.

5.1. Antioxidant activity

ANCS in purple corn possess strong antioxidant capacity, which is influenced by multiple factors, including processing methods, extraction techniques, germination, and corn varieties. *In vitro*, baked purple corn displays higher antioxidant capacity than steamed or boiled samples, while both steaming and baking processes retained a stronger ability to inhibit reactive oxygen species (ROS) in HepG2 cells (Wang et al., 2024). Similar trends were observed during the preparation of purple corn milk and muffins, which was related to the retention of ANCS and other phenolic compounds during the heat processing (Shiekh et al., 2023). Moreover, non-thermal extraction methods, like ultrasound – assisted extraction, produced purple corn pericarp extracts with greater antioxidant activity compared to thermal (microwave - assisted) extraction techniques (Boateng et al., 2023).

Among individual phenolics, ferulic acid and quercetin derivatives, two major phenolic compounds, play a crucial role in the antioxidant activity of purple corn kernels (Galvez Ranilla et al., 2021). Maltodextrin-encapsulated polyphenols from purple corn pericarp exhibit enhanced free radical scavenging activity, likely due to improved preservation of C3G, epicatechin, and phenolic acids during encapsulation (Ali et al., 2024a). In addition, purple corn anthocyanin pigment effectively inhibited lipid oxidation and enhanced the antioxidant stability of light-protected milk during storage (Saikaew et al., 2018).

The antioxidant and cytoprotective effects of purple corn have also been validated in various animal models. In Sprague–Dawley rats, phenolic-rich purple corn extract protected blood cells against cigarette smoke-induced DNA damage by activating the AMPK–Foxo3a–MnSOD signaling pathway (Kim et al., 2021). Supplementation with purple corn pigment (PCP), rich in cyanidin and delphinidin, significantly enhanced antioxidant defense systems in goats, including increased glutathione (GSH) and catalase (CAT) activity, while reducing superoxide and hydroxyl radical levels (Tian & Luo, 2022). Similarly, PCP supplementation significantly increased plasma total antioxidant capacity (TAC), superoxide dismutase (SOD), and glutathione peroxidase (GSH-Px) levels in Chishui black-bone chickens (Luo et al., 2022). Li et al. (2020) investigated the effects of purple corn extract (PCE) on oxidative stress, tissue morphology, and the underlying mechanisms in fluoride-exposed Wistar rats. The results demonstrated that the anthocyanin-rich PCE significantly reduced MDA levels and elevated the SOD levels in the brains of fluoride-intoxicated rats, while mitigating histopathological

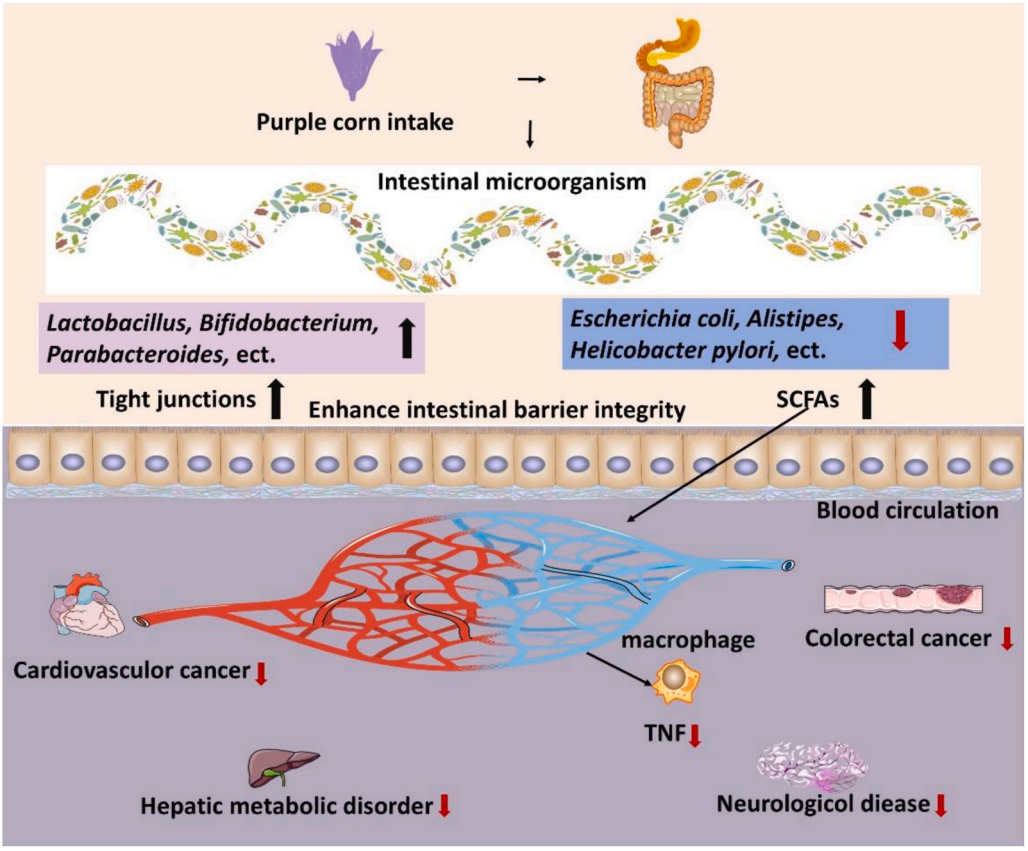

Fig. 2. Purple corn extract modulates the composition and function of the gut microbiota, helping to maintain microbial homeostasis, thereby improving intestinal barrier function and promoting overall health. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

changes and neuronal apoptosis.

Overall, the antioxidant activity of purple corn is strongly associated with the levels of bioactive compounds, including individual ANCS, flavonoids, flavonols, flavanols and phenolic acids, which confer high antioxidant activity both in *in vitro* and *in vivo*.

5.2. Anti-inflammatory effects

Purple corn extracts have demonstrated pronounced anti-inflammatory activity in a variety of cellular models. Water extracts from the pericarp of twenty Apache Red purple maize samples (PMWs) significantly attenuated inflammation in lipopolysaccharide (LPS)-stimulated RAW264.7 macrophages. PMW treatment reduced nitric oxide (NO) production by 13.0–59.5% compared with LPS-treated controls and markedly suppressed the protein levels of tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6), as well as the gene expression of inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2). These effects were largely attributed to the presence of bioactive compounds, including anthocyanins (ANCS), quercetin, kaempferol, and rutin (Q. Zhang et al., 2019b). Pre-treatment with ANCS from purple corn (C3G, Pr3G, and P3G) and protocatechuic acid (PCA) significantly attenuated the activation of NF-κB and MAPK signaling pathways in human chondrocytes stimulated by advanced glycation end products (AGEs), suggesting a protective role against AGE-mediated inflammation and diabetes-associated cartilage degradation (Chuntakaruk et al., 2021). Consistently, purple corn ANCS effectively suppressed the production of pro-inflammatory mediators, including NO and TNF-α, in LPS-induced BV2 microglial cells (Gao et al., 2023). Furthermore, pigmented corn extracts significantly down-regulated the release of C-X-C Motif Chemokine Ligand 10 (CXCL-10) and Soluble Intercellular Adhesion Molecule-1 (sICAM-1) in CaCo-2 cells induced by IL-1β, IFN-γ, digested gliadin, with the underlying mechanisms partially attributed to the disruption of NF-κB signaling (Piazza et al., 2024), highlighting the potential of pigmented corn as a functional ingredient for mitigating intestinal inflammation, particularly in the context of gluten-free diets for celiac disease management (Piazza et al., 2024).

5.3. Anti-obesity properties

With the increasing variety of modern foods and the continuous development of socio-economic conditions, the imbalance between energy intake and expenditure has intensified, leading to excessive accumulation of triglycerides (TG) in the body and resulting in obesity (Capoccia et al., 2025). Reducing obesity rates and improving public health present a significant challenge for both current and future generations. Numerous studies have shown that natural compounds such as phenolic acids, flavonoids, ANCS, terpenoids, carotenoids, and phytosterols can effectively inhibit the activity of digestive enzymes, including amylase, glucosidase, and pancreatic lipase, thereby reducing the digestion of carbohydrates and fats and lowering energy intake (Rajan et al., 2020).

Luna-Vital et al. (2017) reported that a purple corn water extract (PCW) reduced 3T3-L1 adipocyte differentiation by 50% at a concentration of 0.4 mg/mL. Both PCW extracts and purified ANCS (C3G, Pr3G, and P3G) inhibited lipase and fatty acid synthase activity and suppressed peroxisome proliferator-activated receptor γ (PPARγ) transcriptional activity. Similar findings were observed by Zhang et al. (2019b), who reported that twenty PMWs (1 mg/mL) reduced intracellular triglyceride accumulation by 12.9–55.9%, with certain samples also stimulating glycerol release, an effect associated with higher levels

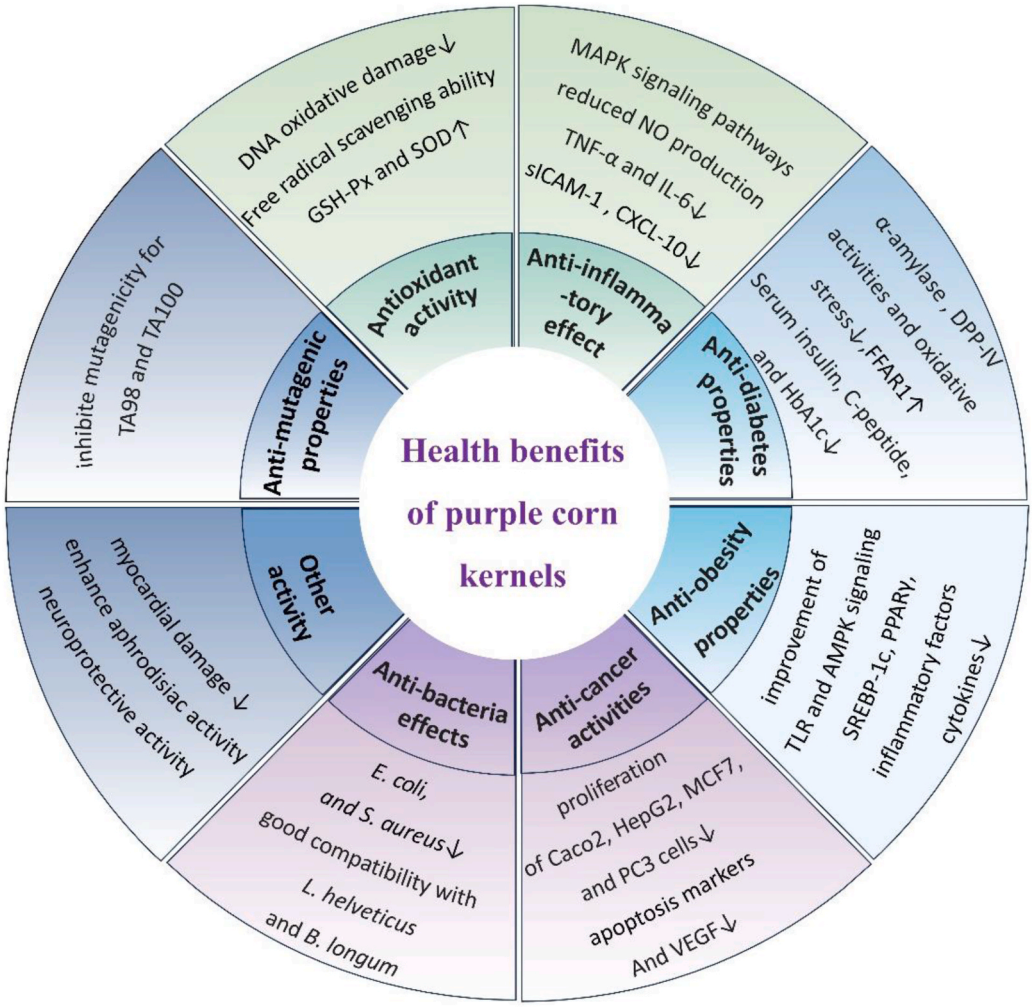

Fig. 3. The beneficial effects of purple corn kernels. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of vanillic and protocatechuic acids. Additionally, Wang et al. (2024) investigated the effects of different heating-processing methods (boiling, steaming, and baking) on purple corn extracts in oleic acid-induced HepG2 cells. Among this methods, baking was the most effective in inhibiting lipid droplet accumulation and reducing excessive intracellular ROS, likely due to the superior retention of ANCS during the baking process (Wang et al., 2024).

In vivo studies corroborate these findings. Tian et al. (2021). reported that anthocyanin-rich purple corn pigment (PCP) could inhibit the accumulation of total cholesterol (TC) in goats and downregulate the expression of ltearoyl-CoA desaturase (SCD) and lipoprotein lipase (LPL) genes in goat muscle tissue. Compared with black rice anthocyanin (9.6%) and black soybean anthocyanin (13.3%), purple corn anthocyanin demonstrated superior efficacy in attenuating body weight gain in obese C57BL/6 mice (16.6%) (Wu et al., 2017). Moreover, supplementation with purple corn pericarp water extract (400 mg/kg) prevented high-fat diet-induced obesity by modulating Toll-like receptor and AMP-activated protein kinase (AMPK) signaling pathways, reducing lipogenesis, and enhancing energy expenditure (Luna-Vital et al., 2020a). Xu et al. (2021) found that PCE in rats supplemented with chia seed oil reduced SREBP-1c and Δ5D gene expression and protected desaturase activity from inhibition by Alpha-linolenic acid (ALA). Similarly, the combination of ANCS and α-linolenic acid (ALA) exhibited pronounced anti-adipogenic effects in Sprague–Dawley rat models (Reyna Gallegos et al., 2018).

5.4. Anti-diabetic effects

Diabetes is a serious chronic disease associated with widespread complications and an increased risk of premature death, placing significant financial strain on national healthcare systems and economies (Saeedi et al., 2020). Increasing evidence indicates that anthocyanins (ANCS) from purple corn exert significant anti-diabetic effects through multiple mechanisms.

In vitro enzyme inhibition assays demonstrated that water extracts from twenty purple maize pericarp samples (PMWs) effectively inhibited α-amylase and dipeptidyl peptidase-4 (DPP-IV), with IC_{50} values ranging from 109.5 to 172.7 μg/mL and 65.5 to 702.7 μg/mL, respectively (Q. Zhang et al., 2019b). In pancreatic β-cell models, purple corn ANCS enhanced glucose-stimulated insulin secretion in INS-1E cells by activating free fatty acid receptor 1 (FFAR1), a key regulator of insulin release (Luna-Vital & Mejia, 2018). Furthermore, ANCS from purple corn have been found to increase hepatic glucose uptake *in vitro*, contributing to the maintenance of glucose homeostasis (Luna-Vital & Mejia, 2018).

There is also extensive research on *in vivo* studies on the anti-diabetic effects of purple corn components. Huang et al. (2015) reported that administration of purple corn extract at doses of 10 mg/kg and 50 mg/kg significantly decreased plasma glucose levels and increase the serum insulin, C-peptide and HbA1c levels in C57BL/KsJ db/db mice in a dose-dependent manner. Similarly, Bhaswant et al. (2017) treated rats with 3.1 mg/kg BW of purple maize powder, finding that ANCS were the

main bioactive compounds in purple maize powder, helping to reverse or attenuate metabolic syndrome symptoms. Overall, these findings suggest that ANCS from purple corn are promising candidates for inclusion in the diet during the management of type 2 diabetes and associated diseases.

5.5. Anti-cancer activities

Cancer has emerged as a significant public health concern, primarily due to its aggressive nature and elevated mortality rate (de Arruda Nascimento et al., 2022). According to the International Agency for Research on Cancer (IARC), one in every five people worldwide might be diagnosed with cancer in their lifetime, making cancer prevention one of the most critical public health challenges of the 21st century. Studies have shown that anthocyanin-rich purple corn extracts exhibit a dose-dependent effect in inhibiting cancer cell viability. Specifically, purple corn pericarp water extract, purple corn resin-purified acidic water extract (PAW), and purple corn PAW extract containing additional ethyl acetate-purified components (PAWE) inhibited the viability of HT-29 and HCT-116 cells in a dose-dependent manner, while exhibiting no toxic effect on normal CCD-33Co cells (Mazewski et al., 2017). Compared with red corn, purple corn extract significantly increased the number of apoptotic cells and had a more pronounced effect on apoptosis markers such as BAX, cyt *c*, and surviving (Mazewski et al., 2017). Furthermore, purple corn extracts significantly reduced the expression of VEGF (Mazewski et al., 2017). These results suggest that anthocyanin-rich purple corn extracts may inhibit human colorectal cancer cell proliferation by inducing apoptosis and suppressing angiogenesis. Urias-Lugo et al. (2015) showed that acidic extracts of blue corn more effectively inhibited the proliferation of breast (MCF7), liver (HepG2), colon (Caco2 and HT29), and prostate (PC3) cancer cells compared with non-acidic extracts, an effect attributed to the high content of cynaroside malonyl-glucoside. Moreover, purple corn extracts exhibited strong antimutagenic activity in the Kado microsuspension assay, inhibiting mutagenicity in Salmonella strains TA98 and TA100, likely due to their high cyanidin-3-glucoside (C3G) content (Loarca-Piña et al., 2019).

Overall, these findings suggest that purple corn, rich in both acylated and non-acylated anthocyanins, may exert protective effects against breast, liver, colon, and prostate cancers by modulating multiple tumor-related signaling pathways. The molecular mechanisms underlying the anti-cancer activity of purple corn kernels are summarized in Fig. 4. As the anti-cancer effects of purple corn have been comprehensively reviewed elsewhere (Lao et al., 2017), and thus, will not be further elaborated upon here.

5.6. Other effects

Beyond metabolic and anti-cancer activities, purple corn extracts exhibit a range of additional bioactivities. Anthocyanin-rich purple corn extract, particularly cyanidin-3-glucoside, has been shown to attenuate doxorubicin-induced cardiotoxicity by reducing myocardial oxidative damage, highlighting its potential as a functional food adjunct during anthracycline chemotherapy (Petroni et al., 2017). In addition, purple corn water extract enhanced aphrodisiac activity by modulating the brain and spinal cord, key areas of the central nervous system controlling ejaculation (Carro-Juárez et al., 2017). Peruvian purple corn, rich in ferulic acid and its derivatives as well as coumaric acid, demonstrates good compatibility with beneficial probiotic lactobacilli, such as *L. helveticus* and *B. longum*. However, it shows no inhibitory effect against the *pathogenic Helicobacter pylori* (Gálvez Ranilla et al., 2017). In food packaging and antimicrobial applications, silver nanoparticles synthesized using purple corn extract and incorporated into chitosan films showed enhanced antibacterial activity against *E. coli, Salmonella, Staphylococcus aureus,* and *Listeria monocytogenes*, outperforming conventional chitosan-based films (Qin et al., 2019). This maybe because 3-month period too short to fully activate the effects of pigmented corn extract, as prebiotics take longer to be utilized by gut bacteria (Trezzi et al., 2025). In addition, polyphenol-rich purple corn extracts have demonstrated potential as cost-effective biopesticides against Lepidoptera pests (Tayal et al., 2020), further expanding the industrial relevance of purple corn beyond food and nutraceutical applications.

6. Industrial applications of purple corn kernels

Purple corn has a wide range of applications in the fields of food, cosmetics, and medicine. For instance, it is utilized in products such as purple corn tea, purple corn-based perfumes, and various skincare

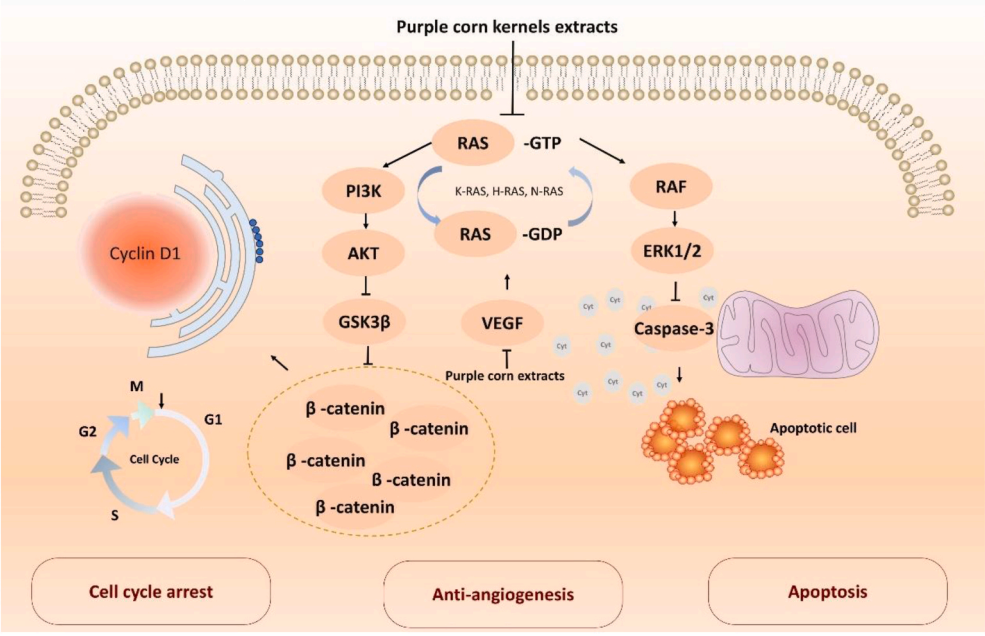

Fig. 4. Anti-cancer mechanism of purple corn kernels extracts, association with cell cycle arrest, anti-angiogenesis, and cell apoptosis. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

formulations. A summary of the reported applications of purple corn is presented in Fig. 5.

6.1. Applications of purple corn in food industry

6.1.1. Purple corn breakfast cereal

Camargo et al. (2024c) developed breakfast cereals using 100%, 75%, 50%, and 25% Andean purple maize whole flour (APM) complemented with yellow corn grits, which enriched the market for healthy and nutritious foods while adding value to local crops. However, in the co-digestion experiment with milk and almond milk, 50% APM breakfast cereals showed lower carotenoid bioaccessibility compared to the 100% yellow corn cereal which mainly due to the high fiber content, low carotenoid levels, and the presence of ANCS (Camargo et al., 2024c). In this context, the industry should focus on developing food products that deliver specific nutrients and bioactive compounds, rather than promoting "superfoods" that do not meet practical nutritional and health goals.

6.1.2. Purple corn gluten-free pasta

The gluten-free purple corn pasta displays noteworthy antioxidant capacity and favorable physical and culinary characteristics. However, sensory analysis revealed that the incorporation of purple corn induced certain unfavorable attributes, including bitterness and grainy texture (Delgado-Pando et al., 2025). Therefore, future formulations of gluten-free pasta using purple corn flour should prioritize strategies to mitigate these sensory drawbacks, specifically addressing the bitterness and granular mouthfeel, to improve overall product quality and consumer acceptance.

6.1.3. Purple corn steamed bread

Guo et al. (2022) prepared purple corn dough by mixing purple corn flour (PCF) with water in different particle sizes produced by low temperature impact mill, followed by yeast fermentation and steaming for 40 min to produce purple corn steamed bread. The PCF with a particle size of 56 μm exhibited textural properties more similar to those of wheat flour, characterized by a smooth surface, regular shape, porous structure, suitable textural characteristics, and a lower digestibility (Guo et al., 2022). Furthermore, this sample also demonstrated strong *in vitro* α-amylase inhibitory activity (Guo et al., 2022).

6.1.4. Purple corn beverage

Purple corn, traditionally grown in the Peruvian Andes, is a key ingredient in "*Chicha Morada*," a typical non-alcoholic beverage (Spessoto et al., 2020). *Chicha de Güiñapo*, made by fermented purple corn, exhibited *in vitro* inhibitory activity against α-amylase and α-glucosidase, which is attributed to its high content of TPC (28.09 to 41.79 mg GAE/100 mL) (Vargas-Yana et al., 2020). Meléndez et al. (2024) developed an instant beverage from fermented purple corn using spray-dry technology.

6.1.5. Purple corn cookies and muffins

Corn flour, which is gluten-free, is used to make muffins or cookies to cater to individuals with celiac disease or gluten intolerance (Slavu (Ursu) et al., 2022). In addition to free-gluten, it brings abundant content of bioactive compounds. Slavu et al. (2022) examined how varying proportions of corn and rice flour influence the phytochemical profile and antioxidant activity of anthocyanin-enriched gluten-free cookie formulations. The results showed that in cookies with 75% addition of purple corn flour, the concertation of ANCS was up to 6.99 ± 0.20 mg C3G/100 g dw, along with an antioxidant activity of 18.46 ± 0.18 mm Trolox equivalents/g dw. In conclusion, from the technology perspective, it has been demonstrated that gluten-free bakery products can be produced. Compared to wheat-based products, these products are characterized by "high in dietary fiber" and "low in saturated fat," while maintaining favorable sensory properties and meeting the dietary needs of individuals with specific health needs.

6.1.6. Purple corn - based film or coat

Currently, purple corn has been used to prepare films or coatings to extend the shelf life of foods. Additionally, the purple corn-based film exhibited pH-sensitive properties and could be further used to monitor the freshness of packaged food. Chen et al. (2023) prepared an antimicrobial indicator film containing purple corn cob anthocyanin and

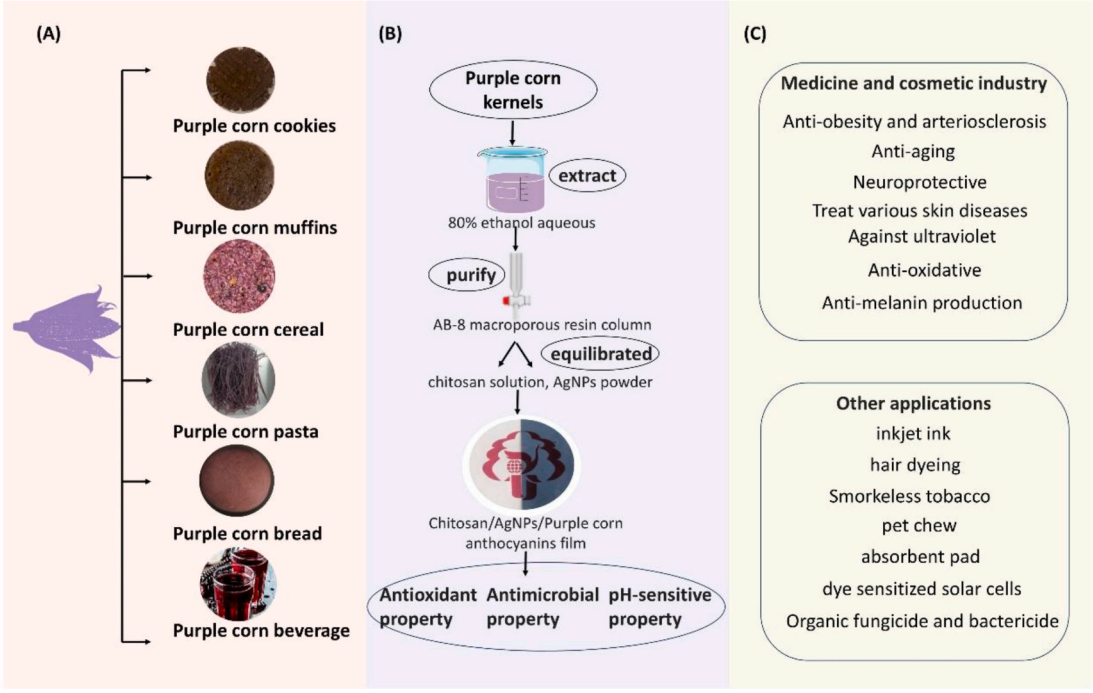

Fig. 5. Applications of purple corn kernels in food products (A) applications of purple corn kernels in food packaging (B); and (C) applications of purple corn kernels in industry products. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

successfully used it to monitor the freshness of pork. Another study showed that the film based on chitosan and microencapsulated anthocyanin powder can also extend the shelf life of blueberries at room temperature (Bustamante-Bernedo et al., 2025). In conclusion, anthocyanin-rich purple corn particles hold great potential as a material for active film production, showing significant promise in industrial applications for food packaging. These films not only help reduce refrigeration costs, but also enhance the safe preservation of fresh food products.

6.2. Applications of purple corn in medicine and cosmetics industry

ANCS from purple corn have been widely investigated as scalable and cost-effective alternatives to synthetic dyes. Natural anthocyanin colorants, including those derived from purple corn, have been successfully incorporated into cosmetic formulations such as lipsticks and evaluated for shelf stability. Among these, formulations dominated by cyanidin-based anthocyanins—such as purple corn anthocyanins—exhibited superior color stability (Westfall & Giusti, 2017). Moreover, preparation of purple corn anthocyanin microcapsules through spray drying exhibited improved photoprotective stability and stronger humidity tolerance, showing potential for applications in the medicine and cosmetics industries (Deng et al., 2023).

In addition to their coloring properties, purple corn extracts possess bioactivities relevant to skin health. A topical cream containing purple corn extract significantly inhibited UV-B–induced increases in matrix metalloproteinase-1 (MMP-1) and prevented collagen degradation in Wistar rats (*Rattus norvegicus*), effects attributed to the combined presence of phenolic acids, vitamin C, and anthocyanins (Wiraguna et al., 2019). Collectively, these findings suggest that purple corn extracts not only function as natural colorants but also offer antioxidant, anti-inflammatory, and tyrosinase-inhibitory activities, highlighting their strong potential for use in cosmeceutical products aimed at preventing photoaging and hyperpigmentation.

7. Potential toxicity

When consuming purple corn, the potential toxicity should also be considered. Literature about the potential toxicity of purple corn kernels is rare. In subacute toxicity experiment, purple corn color, containing 26.4% of ANCS, 57.7% of polyphenol and glucose and 10% of citric acid, was fed to F344/DuCrj rats at the dose of 0%, 0.5%, 1.5% and 5.0% for 90 days. A dose-dependent darkening of the digesta and excreta was observed, but no significant changes in hematology, clinical chemistry, or histopathological conditions (Nabae et al., 2008). Based on these results, the no-observed-adverse-effect level (NOAEL) for purple corn color was established at 5.0% of the diet for both sexes, corresponding to daily intakes of 3542 mg/kg body weight for males and 3849 mg/kg body weight for females (Nabae et al., 2008).

In another study, cyanidin-rich extracts from *Zea mays L. ceritina Kulesh.* and delphinidin-rich extracts from *Clitoria ternatea L.* were used to form four anthocyanin complexes. At a concentration of 1 mg/ml, none of the four anthocyanin complexes showed toxicity to Human Gingival Fibroblasts cells, which provides a potential candidates for the oral health–related products (Limsitthichaikoon, 2015).

To date, virtually all research on purple corn derived-polyphenols has focused on the minimum dose needed to demonstrate beneficial health effects, while there is scant evidence regarding the potential toxicity of these polyphenols at higher doses. As shown in Table 2, although the studies indicate that purple corn extract is safe, most of the research is limited to animal or cell experiments. Only one human study reported that taking 18 mg of concentrated anthocyanin per person per day for three weeks was not harmful to humans and may have beneficial effects on blood pressure control (Finkel et al., 2013). Therefore, despite the substantial body of evidence supporting the biological activities of purple corn, additional well-designed clinical studies are required to confirm its safety profile and to establish scientifically justified dosage recommendations for human nutraceutical applications.

8. Conclusion and perspective

Purple corn, characterized by its rich content of phenolic acids and flavonoid compounds, has attracted increasing attention from both the scientific community and the public. In recent decades, research on the components and bioactivities of purple corn has significantly increased, with a primary focus on its antioxidant, anti-inflammatory, and anticancer activities both *in vitro* and *in vivo*. This review systematically analyzed a wealth of studies exploring the composition and bioactivity of compounds in purple corn, as well as the factors influencing the bioavailability of purple corn and its active compounds. However, the mechanisms underlying the health benefits of purple corn, the structure-activity relationship between its phytochemical components and bioactivity, and the impact of factors such as processing methods, varieties, and species on its bioactivity remain areas requiring further investigation.

Although studies on the anticancer effects of purple corn have predominantly demonstrated that compounds derived from purple corn extracts can increase cytotoxicity in cancer cells. the underlying mechanisms of its anticancer ability need further explore. Beyond these, animal and in *vitro* studies indicate that purple corn extracts may exert beneficial effects on inflammatory disorders, liver and cardiovascular diseases, obesity, and neurological conditions. Nevertheless, human trials are still needed to confirm these potential health benefits.

In addition, this review discussed the applications of purple corn in various fields, including food, pharmaceuticals, and cosmetics. Furthermore, purple corn has also been utilized in the production of pigment-sensitive solar cells, insecticides, and pet chew, among other industrial applications, which demonstrate that purple corn is not only applicable in food and pharmaceutical, but can also be used in various industrial fields.

However, it is important to note that ANCS, the active components in purple corn, exhibit rapid degradation and low bioavailability, which limits the functional potential of purple corn. Technologies such as nanoencapsulation and film coating have been widely applied to protect ANCS and other beneficial polyphenols. Therefore, further research could explore the effects of nano-structured formulations containing purple corn bioactive compounds on cancer cells, thus expanding the potential application of purple corn bioactive compounds in nanomedicine.

Moreover, future research should also focus on expanding the scope of *in vivo* studies to complement and enrich the current in *vitro* research. Toxicological studies on purple corn are still limited, making it necessary to further explore the potential toxicity of purple corn extracts to provide a foundation for the use as dietary supplements. Finally, more clinical trials are needed to understand the health benefits of purple corn in humans, which will facilitate its broader application in functional foods, health supplements, and even pharmaceuticals.

Credit role

Qingwei Cao: conceptualization, investigation, writing–original draft. **Haixia Hu:** conceptualization, investigation, visualization, writing–original draft. **Chen Ge**: visualization. **Bei Yang:** writing – review and editing. **Zexiu Qi:** writing – review and editing. **Xiumin Chen:** visualization. **Yasmany Armas Diaz:** Conceptualization, investigation, writing – review and editing. **Carlos Luis Rabeiro Martinez:** writing – review and editing. **Danila Cianciosi**: data curation, writing – review and editing. **Jianbo Xiao:** data curation, writing – review and editing. **José L. Quiles:** visualization. **Francesca Giampieri:** conceptualization, writing – review and editing, supervision. **Maurizio Battino:** conceptualization, funding acquisition, project administration, supervision.

Table 2
Activity of purple corn kernels in *in vitro* and *in vivo* (2015-2025).

in vitro	Function	Purple corn	Experimental models	Dose & time	Mechanisms	Reference
	Antioxidant	*Zea mays L. var. ceratina* (0, 50% and 95% hydro-alcoholic solution)	H_2O_2 induced -SH-SY5Y cells	31.25 and 62.5 μg/mL, 24 h	ROS↓, MDA↓, CAT↑, SOD↑, GSH-Px↑, pERK1/2/ERK1/2↑, Neuroprotection↑, Apoptosis↓	Mairuae et al. (2024)
		Zea mays L. Scagliolo Rosso and Rostrato di Rovetta (ethanol:water 60:40 (v/v) solution for 4 and 16 h)	H_2O_2 induced-CaCo-2 cells	200 μg/mL, 48 h	ROS↓	Piazza et al. (2024)
	Anti-obesity	Four types of purple corn (boiling, steaming and baking)	Oleic acid induced- HepG2 cells	40 μg/mL purple corn (before and after digestion), 12 weeks	Oil red o and Nile blue methods (Lipid droplets↓, white and shiny oil drops↓), ROS↓	Wang et al. (2024)
		Pure C3G, Pr3G, P3G and purple corn pericarp water extract (PCW)	3T3-L1 preadipocytes differentiation	0.4 mg of dry sample/mL PCW (50.3 μM eqC3G) or 50 μM of either C3G, Pr3G, or P3G, 24 h	Adipocyte differentiation↓, PPARγ↓, TG↓, lipase activity↓, fatty acid synthase↓, endocan, fetuin A, IGFBP-3↓, LIF and VEGF↑, ROS↓, GLUT4↑	Luna-Vital et al. (2017)
		Anthocyanin-rich fractions from 20 selected purple maize pericarp (PMW)	TNF-α-induced 3T3-L1 preadipocytes differentiation	1 mg/mL of each PMW, 24 h	MCP-1↓, TG↓, Adiponectin↑, lipid content↓, PPARγ↓, ROS↓, glucose uptake↑	Q. Zhang et al. (2019b)
	Anti-inflammatory	*Zea mays L. Scagliolo Rosso* (ethanol:water 60:40 (v/v) solution for 4 and 16 h)	IL-1β (10 ng/mL), IFN-γ (10 ng/mL), and *in vitro* digested gliadin (1 mg/mL) induced-CaCo-2	rang from 50 to 200 μg/mL, 6 h	CXCL-10↓, sICAM-1↓, IL-8↓, NF-κB↓,	Piazza et al. (2024)
		Zea mays L. Chiang Mai, Thailand (0.1 N HCl and methanol (20:80)) and C3G, Pg-3-glc, P3G	25 μg/ml of AGEs induced- porcine articular cartilage from the metacarpophalangeal joints of 6-8 months old pigs	6.25-25 μg/ml and 2.5-10 μM, 35 days	s-GAG↓, HA ↓, uronic acid↑, mRNA MMP-1, -3 and -13↓, NF-κB and MAPK signaling pathway: phosphorylation levels of IKK, IκB p65, ERK, p38 and JNK↓	Chuntakaruk et al. (2021)
		Anthocyanin-rich fractions from 20 selected purple maize pericarp (PMW)	LPS- induced RAW264.7 macrophages	1 mg/mL of each PMW, 24 h	iNOS↓, COX-2↓, PGE_2 ↓, ↓, NO↓, IL-6↓,	Q. Zhang et al. (2019a)
		Anthocyanin-rich purple corn (PCO, 60% aqueous ethanol solution (v/v) containing 3 mol L^{-1} HCL)	LPS-stimulated BV2 cells	50, 100, and 200 μg/mL, 24 h	NO↓, TNF-α↓, proteins expression: TLR4↓, MyD88↓	Gao et al. (2023)
	Anti-diabetes	Pure ANC (C3G, P3G, Pr3G, D3G, C3G-P, and CF-P) and purple corn pericarp (water solution, PCW)	Two cellular systems: co-culture Caco-2, HepG2 and co-culture Caco-2, iNS-1E cells	1 to 100 μM of pure ANC or 0.125-1 mg/mL PCW, 24 h	epithelial glucose transport↓, insulin secretion↑, proteins expression: FFAR1↑, PLC↑, PKD↑, IP production↑, glucose uptake↑, activated GK↑, AMPK↑, PEPCK↓	Luna-Vital and Mejia (2018)
	Anti-bacterial	*Zea mays L.* from the Brunca and Chorotega regions of Costa Rica (Six solvent mixtures were evaluated)	Kirby–Bauer method	100 mg/mL, -	relative percentage of the diameter of the inhibition zone: *(Staphylococcus aureus*↓, *Escherichia coli*↓, *Bacillus subtilis*↓)	Syedd-León et al. (2020)
		Purple corn accession *AREQ-084*	*L. helveticus, B. longum and H. pylori*	10 mg/mL, 48 h	No inhibition of beneficial probiotic lactic acid bacteria such as *L. helveticus* and *B. longum*	Gálvez Ranilla et al. (2017)
	Cardioprotection	Pure C3G and purple corn extract	DOX induced- HL-1 cells	125 μM, 48 h	ROS↓, mRNAs renin1, ACE↓, no effect on tumor MCF-7 and HeLa cell lines	Petroni et al. (2017)
	Anti-cancer *Colorectal cancer*	Pure P3G, C3G, and Pr3G, purple corn pericarp water extract (PW), Purple corn resin-purified acidified water extract (PAW) and Purple corn PAW extract with additional ethyl acetate purification (PAWE)	HT-29, HCT-116, and CCD-33Co	0.25-10 mg/mL, 24 h	HT-29 and HCT-116 cell proliferation↓, HT-29 cells apoptosis↑, Bcl-2↓, Cytochrome C↑, angiogenesis↓, VEGF↓, HT-29 cells Abl2↓, TRAIL r2/dr5↑, Survivin↓	Mazewski et al. (2017)
in vivo	Anti-oxidative	Anthocyanin-rich maize purple plant pigment	Eighty healthy weanling Wistar rats (50% male) (100 ppm fluoride ion (F−))	5 and 10 g/kg, 12 weeks	MDA↓, SOD↑, Neuronal apoptosis↓	Li et al. (2020)
		Anthocyanin-rich purple corn extract (PCE)	360 healthy Chishui black-bone hens	120, 240, and 360 mg/kg PCE, 60 days	SOD↑, TAC↑, GPX↑, MDA↓	Li et al. (2023)
		PCE	18 Qianbei Ma wether kids	0.5, 1 g/d PCP, 60 days	glutathione↑, POD ↑	Tian, et al. (2021)
		Purple corn pigment (PCE)	288 growing Chishui black-bone chickens	80, 160, and 240 mg/kg PCP, 60 days	TAC↑, SOD↑, GSH-Px↑, CAT↑ peroxidase↑	Luo et al. (2022)

(*continued on next page*)

Table 2 (*continued*)

in vitro	Function	Purple corn	Experimental models	Dose & time	Mechanisms	Reference
		Purple corn pigment (PCE)	18 Qianbei pockmarked wether goats	0.5, 1 g/d PCP, 60 days	GSH↑, CAT↑, POD↑, DPPH↑, O_2^-↑, OH↑	Tian and Luo (2022)
		Zea mays var. kculli	24 male Sprague–Dawley (SD) rats (cigarette smoking)	10/mg/kg/day, 0.3 ml water solution, 7 days	MO cells↑, EO cells↑, BA cells↑, immunofluorescence expression profiling for two markers (γ-H2AX and Foxo3a) staining-positive cells↓, AMPK-Foxo3a-MnSOD↑	W.-S. Kim et al. (2021)
	Anti-obesity	Angelina's Gourmet purple maize pericarp water extraction (PPE)	Forty male C57BL/6 mice (6 weeks old) (high-fat diet, HFD)	200, 500 mg PPE/kg body weight, 12 weeks	food efficiency ratio↓, weight gain↓, plasma insulin content↓, HOMA-IR↓, FBG↓, TG↓, TNF-α↓, IL12p70↓, liver lipid accumulation ↓, adipocyte hypertrophy↓, genes related to glucose metabolism↓,	Luna-Vital et al. (2020b)
		Anthocyanin-rich purple corn pigment (PCP)	18 Qianbei Ma wether kids	0.5, 1 g/d PCP, 60 days	T-CHO, total cholesterol↓, Cr, creatinine↓, PPARγ mRNA↓, LPL↑, SCD ↓,	Tian et al. (2021)Tian, Luo, and Wang (2021)
		Anthocyanins from purple corn (APM)	60 male C57BL/6 mice (high-fat diet)	100 and 400 mg/kg APM, 12 weeks	weight gain↓, Lee's index↓, epididymal fat mass↓, TG↓, TC↓, AST↓, gene expression: C/EBPα, PPARγ, SREBP-1c, ACC, FABP4and FAS↓, PPARα, PRDM16, PGC1α and UCP1↑, proteins expression: p-AMPK↑, ACC↓, microbial diversity↑	Xu et al. (2021)
		Anthocyanin-rich purple corn extract (PCE)	Thirty-six (36) female Sprague-Dawley rats (olive oil, chia oil)	1% PCE, equivalent to 401 mg of anthocyanins/ food kg, 10 weeks	Gene expression of SREBP-1c↓, Δ5D↓, enzymatic activity of Δ5D and Δ6D↑, Total SFA↑, C18:1, 9↑, C 20: 5, n-3 (EPA) ↑	Reyna Gallegos et al. (2018)
		Anthocyanin-rich purple corn methanol/ formic acid (9:1, v/v) extract (PCE)	72 male C57BL/6 mice (high-fat diet, HFD)	200 mg/kg, 12 weeks	body weights↓, serum: TG↓, TC, LDL-C↓, MDA l↓, HDL-C↑, hepatic lipids: TC↓, oxidative stress↓, SOD↑, GPx↑, fatty acid decomposition↑, inflammation genes↓, TNF-α↓, IL6↓, NF-κB↓, iNOS genes↓	Wu et al. (2017)
	Anti-diabetes	Dried purple corn kernels (PCE, 30% ethanol-water solution)	C57BL/KsJ *db/db* mice	10 or 50 mg/kg PCE, 8 weeks	Plasma glucose↓, serum insulin↑, C-peptide↑, HbA1c↓, adiponectin↑, AUC↓, glucagon↓, HDL-cholesterol↑, TG↓, β-cell damage↓, mRNA expression G6pase↓, PEPCK↓, GLUT4↑, Phosphorylation of AMPK↑	Huang et al. (2015)
		Purple waxy corn and ginger extracts at a ratio of 1: 4 (50% hydroalcoholic solvent)	40 male Wistar rats (STZ induced-diabetes)	50, 100, and 200 mg kg^{-1} BW, 10 weeks	lens opacity↓, opacity index↓, severity of cataract↓, retinopathy↓, TRT↑, NG↑, velocity↑, MDA↓, SOD↑, CAT↑, GPx↑, AR↓	Thiraphatthanavong et al. (2014)
	Anti-metabolic syndrome	purple maize (PM) flour	72 male Wistar rats (fed a maize starch (C group) or high-carbohydrate, high-fat diet (H group))	50 g/kg, 8 weeks	PM vs. H group: Energy intake↑, Body weight↓, Visceral adiposity index↓, Body mass index↓, Tissue wet weight↓, AST↓, ALP↓, Plasma leptin↓, Plasma insulin↓, OGTT-AUC↓, FBG↓, TC↓, TG↓, NEFA↓, Systolic wall stress↓, cardiac output↓, diastolic↓, stroke volumes↓, heart rate↓, isolated Langendorff heart↓, LV stiffness↓, LV dP/dt↑, tissue morphology appeared normal↑, acetylcholine responses↑	Bhaswant et al. (2017)
	Cardioprotection	Pure C3G and purple corn extract	24 female C57BL/6J mice (25 mg/ kg body weight of DOX)	Special diets were produced by replacing the maize content (29%) from a standard diet, 74 days	Mortality↓, myofibrillar damage↓,	Petroni et al. (2017)
	Aphrodisiac Activity	aqueous crude extract of purple corn	Sexually vigorous male Wistar rats	25, 50, and 75 mg/kg, 30 min	intromission latency↓, intromissions↑, ejaculation latency↓, postejaculatory interval↑, Fictive Ejaculation↑, number of GMPEs↑,	Carro-Juárez et al. (2017)

Note: Hydrogen peroxide (H_2O_2), lipopolysaccharides (LPS), monocytes cells (MO), eosinophils cells (EO), basophils cells (BA), peroxidase (POD), peroxisome proliferator-activated receptor gamma (PPARγ) mRNA, lipoprotein lipase (LPL), stearoyl-CoA desaturase (SCD), advanced glycation end products (AGEs), sulfated glycosaminoglycan (s-GAG), hyaluronic acid (HA), cyanidin-3-glucoside (C3G), pelargonidin-3-glucoside (Pg-3-glc), peonidin-3-O-glucoside (P3G), doxorubicin (DOX), area under the curve (AUC), total cholesterol (TC), triacylglycerol (TG), high-density lipoprotein (HDL), low-density lipoprotein (LDL), free fatty acid receptor-1 (FFAR1), phospholipase C (PLC), protein kinase D (PKD), inositol monophosphate (IP), phosphorylation of AMP-activated protein kinase (p-AMPK), phosphoenolpyruvate carboxykinase (PEPCK), tumor necrosis factor α (TNF-α), genital motor pattern of ejaculation (GMPE), alkaline phosphatase (ALP), alanine transaminase (ALT), aspartate transaminase (AST), oral glucose tolerance test-area under the curve (OGTT-AUC), non-esterified fatty acids (NEFA), left ventricular (LV), Crohn's disease and ulcerative colitis (IBD), Crohn's Disease (CD), Ulcerative Colitis (UC), insulin-like growth factor-binding protein 3 (IGFBP-3), leukemia inhibitory factor (LIF), monocyte chemoattractant protein-1 (MCP-1), prostaglandin E2 (PGE2), interleukin-6 (IL-6), aldose reductase (AR), total retinal thickness of retina (TRT), ganglion cell layer (NG), CCAAT/Enhancer-binding Protein α (C/EBPα), peroxisome proliferator-activated receptor γ (PPARγ), sterol regulatory element binding protein 1c (SREBP-1c), Acetyl-CoA carboxylase (ACC), fatty acid synthase (FAS), hormone-sensitive lipase (HSL), peroxisome proliferator-activated receptor α (PPARα), peroxisome proliferator-activated receptor gamma coactivator 1α (PGC1α), uncoupling protein 1(UCP1), PR domain containing 16 (PRDM16), fatty acid binding protein.

Conflicts of interest

The authors declare no conflicts of interest.

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Data availability

No data was used for the research described in the article.

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