



Molecular and Functional Aspects of Anthocyanins: A Narrative Review on their Antioxidant and Anti-inflammatory Mechanism

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Abstract

Anthocyanins are bioactive compounds found in fruits which show a significant effect on biomarkers of inflammation and decrease redox stress. The current narrative review consists of anthocyanins and their different subcomponents like cyanidin, delphinidin consumption in association with inflammation, oxidative stress and anticancer activities. This study was conducted to comprehensively explore their molecular and functional aspects, with a focus on their mechanisms related to antioxidant and anti-inflammatory actions. The data was analysed based on the PRISMA framework, and the search was carried out on Google Scholar, and Pubmed, with primary focus on studies employing human cell culture model and human clinical trials. The data was examined, and the main outcomes identified as anti-inflammatory activities via reduction of IL-1 and IL-6, C-reactive protein, increase in gene expression, and anti-cancer activities, increase in HDL cholesterol, and increase in Interleukin-10 mRNA concentration. Consumption of anthocyanin extracts showed positive results; a dose-dependent relation was witnessed higher doses are more effective in short duration.



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Keywords

Anthocyanins;
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Immunity.

Abbreviations

		IL-1	Interleukin-1
		IL-6	Interleukin-6
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses	IL-10	Interleukin-10
		HDL	High density lipoproteins

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mRNA	Messenger ribonucleic acid	SP	SARS-CoV-2
Cy3Gal	Cyanidin-3-galactoside	NLRP3	Nucleotide-binding domain
C3G	Cyanidin-3-glucoside	leucine-rich	containing family
D3G	Delphinidin-3O-glucoside	pyrin domain	containing-3
P3G	Peonidin-3-glucoside	ASC	apoptosis-associated speck-like protein
NF-κB	Nuclear factor-kappa B	IL-8	Interleukin-8
TNFα	Tumor necrosis factor alpha	EC	Endothelial cell
HaCat	High sensitivity of human epidermal keratinocytes	LPS	Lipopolysaccharide
H ₂ O ₂	Hydrogen Peroxide	8-OHdG	8-hydroxydeoxyguanine
ROS	Reactive Oxygen Species	8-iso-PGF2α	8-iso-prostaglandin F2α
Nrf2	Nuclear factor erythroid 2-related factor 2	MDA	Malondialdehyde
HFD	High fat diet	BMI	Body Mass Index
NOX	Nicotinamide adenine dinucleotide phosphate (NADPH)-oxidase	CRP	C-reactive protein
ERK	extracellular signal-regulated kinase	CVD	Cardio vascular disease
PD-L1	Programmed Cell Death Ligand 1	FBG	Fasting blood sugar
HCT	Hematocrit	TG	Triglyceride
LDL	Low density lipoproteins	MCP-1	Monocyte chemoattractant protein-1
HepG2	Hepatoblastoma	IL-10	Interleukin-10
SOD	Superoxide dismutase	NK	Natural killer cells
VEGF	Vascular endothelial growth factor	Aix	augmentation index
		ASP	aortic systolic pressures
		T2DM	Type 2 diabetes mellitus

Introduction

Anthocyanins found in plant material or their fruits have been widely consumed in various geographical regions. Anthocyanins are water-soluble plant-derived subgroups of flavonoids accountable for the pigmentation of red, purple, and blue, also present in a glycosylated form exhibiting antioxidant activities, a potential dietary component for nutritional management in various health disorder.¹⁻⁴ The term anthocyanin is a fusion of two Greek words: anthos, which means "flowers," and kyanos, that means "dark blue".⁵ Common anthocyanins include pelargonidin, cyanidin, peonidin, delphinidin, petunidin, and malvidin.⁶

Anthocyanins are prevalent in blue and red vegetables and fruits, with their concentrations in plants significantly differing among species, influenced by variety or cultivar, geographic location, climate, agricultural practices, harvest timing, processing, seasonal fluctuations, storage conditions, ripening, temperature, and light exposure.⁷ Blue, red, and purple berries, plums, apples, grapes, cherries, cabbage, and foods with high concentrations of organic colourants are dietary sources of anthocyanins.⁸ Glycosylation

makes anthocyanins more soluble and bioavailable. Additionally, it affects their antioxidant activity and possible health advantages by influencing how they are incorporated, mobilized and utilized in the body. Acetylation improves anthocyanin stability, particularly in the face of environmental stressors such as light, heat, and pH fluctuations. Their biological activity may be prolonged as a result of their increased pigment efficacy and resistance to deterioration. These alterations improve the biological and functional qualities of anthocyanins, including their antioxidant and anticancer capabilities.⁸

According to a number of studies, anthocyanins have strong antioxidant qualities that allow them to counteract the body's dangerous free radicals and shield cells from oxidative damage.⁹⁻¹² Anthocyanins contain anti-inflammatory properties that might be useful in the prevention and management of chronic inflammatory illnesses.¹³⁻¹⁵ Epidemiological studies indicate that anthocyanin intake reduces the risk of diabetes, arthritis, cardiovascular disease, and cancer, attributable to their antioxidant and anti-inflammatory effects.¹⁶⁻¹⁹ Anthocyanins also benefit eye health, particularly when it comes to issues

caused by diabetic retinopathy — high serum blood glucose levels and eye-related disorders macular degeneration.^{20,21} Research shows that ingesting foods high in anthocyanins may boost cognitive function, improve memory, and have a beneficial influence on several neurodegenerative illnesses, which is especially significant in the context of an aging population.^{22,23}

There are several research papers explaining the role of anthocyanins as anti-inflammatory and anti-cancer as a whole. Comprehensive study on dose dependent cell line and clinical trial related to molecular and functional aspect as antioxidant and anti-inflammatory still not clear. Functional pathway including dosage and duration may help to optimize maximum level of anthocyanin consumption for achieving optimal health benefits. This study was particularly conducted to explore their molecular and functional aspects, with a focus on their mechanisms related to antioxidant and anti-inflammatory actions. This article will examine the primary origin of anthocyanins, the mechanisms by which they particularly act on inflammation and cancer evaluating the most recent scientific research including in-vitro and in-vivo evidence supporting the role of anthocyanins in modulating oxidative stress, inflammation, and cancer prevention. Our primary focus will be anthocyanins and their subcomponents consumption in association with inflammation and anticancer activities in scientific studies.

Materials and Methods

We conducted a literature search on the effect of anthocyanins on inflammation and cancer. The research was carried out by searching for specific keywords, such as “Anthocyanins, delphinidin, cyanidin, anticancer, anti-inflammatory, immunomodulation” on search engines Pubmed and Google Scholar. Literature published from the years 2013 to 2024 was included with primary focus on studies employing human cell culture model and human clinical trials. The first selection was based on title and abstract screening. Studies reporting specific outcomes such as a dose-dependent decrease in ROS production, induction of early apoptosis in cancer cell lines, promotion of endothelial cell permeability, modulation of cell-cell adhesion and facilitation of trans endothelial migration and activation of the antioxidant defence

system were included. Studies with an experimental placebo control are also considered for inclusion. Animal studies involving rodents and *Drosophila* are excluded from this review. Studies using anthocyanins in combination with other polyphenols are also excluded. Research lacking a control group is not considered. Studies published in languages other than English as well as dissertations, review articles and book chapters are excluded from this review. Some publications were discarded owing to inconsistencies with the subject, or generic material that did not specifically address the connection under study. After analyzing and reviewing the extracted research articles, the data was compared for reliability.

Results

Chemical Structure

Anthocyanins are flavonoids that give vegetables, flowers, and fruits their blue, red, and purple, colours.²⁴ They provide several health advantages and protect plants from environmental hazards. Plant pigments are present in vacuoles, often in fruits and flowers as granules ranging from 3 to 10 μm in diameter.²⁵ Anthocyanins are glycosides composed of a sugar molecule an aglycone (anthocyanidin).²⁶ Their chemical structure determines their biological qualities and colour. Anthocyanins are composed of three rings: two aromatic rings (A and B) and one heterocyclic ring with oxygen (C) of cationic nature. They frequently exist as flavylium (2-phenylchromene). The C15 skeleton is composed of a chromate ring that contains a second aromatic ring B in position 2 (C6-C3-C6). The flavylium cation is the basic structure of anthocyanidins.²⁷ The model structure is shown in Figure 1.

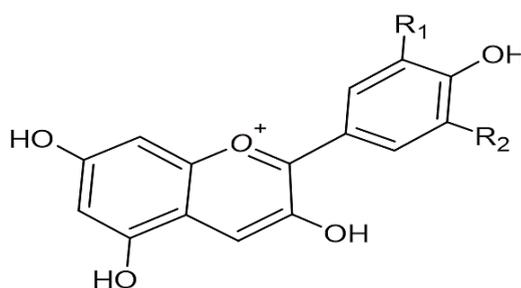


Fig. 1: Basic chemical structure of anthocyanins (created with ChemSketch)

Anti-inflammatory and Antioxidant Effect Anthocyanin

The free radical scavenging capacity of anthocyanins is significantly affected by their chemical structure, and not all of them exhibit comparable activities in scavenging a variety of Reactive Nitrogen Species (RNS) and ROS. The antioxidant capacity of anthocyanins is contingent upon the basic structural orientation of the compound, as the ring orientation determines the ease with which a hydrogen atom from a hydroxyl group can be donated to a free radical and the anthocyanin's ability to support

an unpaired electron.²⁸ The degree and position of hydroxyl groups in the B ring, together with the degree and location of methoxyl groups, affect the stability, reactivity, and subsequently the antioxidant properties of anthocyanins.²⁹ NF- κ B cells are essential in the regulation of genes associated with immunity and inflammation. It has been shown to enhance the invasive phenotype and transcription of oncogenes in cancer cells.³⁰ Free radical scavenging and inflammation modulation are the mechanisms of anthocyanins for cancer prevention.

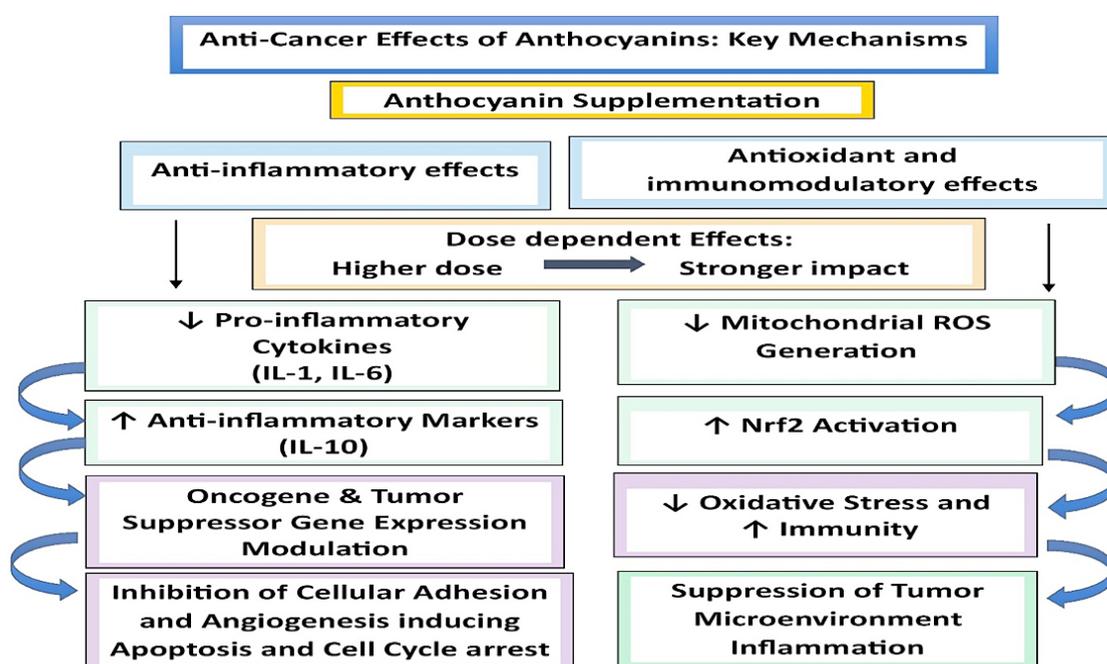


Fig. 2: Anti-cancer mechanism of action of Anthocyanins

The diagram illustrates the key mechanisms through which anthocyanins exert anti-cancer effects, primarily via anti-inflammatory, antioxidant, and immunomodulatory pathways. These effects are dose-dependent, meaning higher doses lead to a stronger impact.¹ **1. Anti-Inflammatory Effects:** Anthocyanins reduce pro-inflammatory cytokines such as IL-1 and IL-6, which are involved in cancer progression. They also increase anti-inflammatory markers like IL-10, promoting an immune response that helps suppress tumour growth.² **2. Antioxidant & Immunomodulatory effects:** Anthocyanins reduce mitochondrial ROS generation, thereby preventing oxidative stress-induced DNA damage. They activate

the Nrf2 pathway, enhancing antioxidant defense mechanisms and boosting immune function.³ **3. Gene Expression & Cancer Suppression:** Anthocyanins modulate oncogene and tumor suppressor gene expression, influencing cell proliferation and apoptosis. They inhibit cellular adhesion and angiogenesis, leading to cell cycle arrest and apoptosis (programmed cell death) which are crucial for halting tumour progression. Additionally, anthocyanins suppress tumour microenvironment inflammation, a key factor in cancer metastasis.

Increasing evidence from randomized controlled trials (RCTs) and mechanistic studies confirms

anthocyanins' potential to prevent oxidative stress and inflammation by modulating important signaling pathways, such as Nrf2 and NF- κ B. Current study evaluates the effects of anthocyanins on oxidative stress, inflammation, and metabolic health using both *in-vitro* and *in-vivo* models. The findings are categorized into cellular responses, and human

trials, which explore anthocyanin supplementation's impact on human health. The key outcomes focus on anthocyanins' ability to modulate inflammatory signaling, enhance antioxidant defences, regulate lipid metabolism, and improve cardiovascular function.

Table 1: Summary of antioxidant and anti-inflammatory effect of Anthocyanin Extracts on cell cultures

Model	Intervention	Findings	Reference
TNF α induced Endothelial cell	A mixture of Cy3Gal, C3G, cyanidin-3-arabinoside, D3G, P3G and 4-hydroxybenzaldehyde	↓trans endothelial migration, monocyte adhesion and modulation of genetic expression	³¹
HaCat keratinocytes cell line	Hibiscus syriacus L extract	↓H ₂ O ₂ -mediated apoptosis, ↓mitochondrial ROS generation, maintaining mitochondrial membrane potential, and activating Nrf2	³²
Caco-2 intestinal cells	Wild blueberry extract	IL-1 β -induced NF- κ B activation in intestinal epithelial and ↓Caco-2 cells dose-dependently	³³
Cancer cell lines	Black rice extract (P3G + C3G)	Dose-dependent ↓cellular proliferation. ↓Apoptosis in cell lines.	³⁴
Oxidant model	Purple rice extract	↓Inflammation in chondrocytes via ↓NF- κ B signalling	³⁵
Cancer cell line	Purple tea shoots extract	Expression of apoptotic fragment formation and nuclear compaction in affected cells. Induction in mononuclear cell proliferation	³⁶
Cancer cell line	L. caerulea 'Beilei' fruit extract	Induce late apoptosis to early apoptosis. ↓Cell division G2 /M phase differentiation and proliferation	³⁷
Oxidant model	C3G and D3G	Protect GI physiology in HFD-induced obesity ↓Caco-2 monolayer permeabilization, ↑NOX1/4, and NF- κ B/ERK activation caused by tumor necrosis factor alpha.	³⁸

Cancer cell line	C3G and D3G	↓Expression of the PD-L1 protein in HCT-116 cells and the intensity of PD-L1 fluorescence by 39%. Induce apoptosis in HTC cell lines.	39
Cancer cell line	Extract from strawberries	↓Triglycerides and LDL-cholesterol and ↑HepG2 cell redox status	40
High glucose-induced human retinal capillary endothelial cells	Extract from blueberry	↓ROS production, by ↑SOD activity. ↓VEGF expression and Akt pathway	41
A549-lung cells and THP-1 macrophages	Extract from black pigmented rice	↓SP-induced inflammation by ↑NF-κB and ↓inflammasome-dependent inflammatory pathway proteins (NLRP3, ASC, and capase-1).	42
Epithelial cell	C3G	↓TNF-α-induced nuclear translocation of NF-κB and IL-8 gene expression in Caco-2 cells.	43
Cancer cell line	Fermented grape and strawberry extract	↑Apoptosis by regulation of the Caspase-3 pathway in HT-Colon cancer cells.	44
Endothelial cells	Blueberry lyophilized extract	↑EC proliferation, a key step in angiogenesis and wound healing.	45
Infection model hepatitis C virus (HCV)	Delphinidin	↓Viral envelope inhibition of Hepatitis C entry.	46
Oxidative cell model	Native Chilean Berries Extract	A dose-dependent ↓oxidation	47
Whole blood culture with LPS	Pelargonidin-3-O-glucoside and its metabolites	No significant activity oxidative burst	48

Endothelial and Keratinocyte Models

Anthocyanins have demonstrated significant anti-inflammatory and antioxidant effects in various cellular models (Table 1). In a TNF-α-stimulated endothelial cell model, a mixture of anthocyanin extracts (Cy3Gal, C3G, cyanidin-3-arabinoside, D3G, P3G, and 4-hydroxybenzaldehyde) inhibited

trans-endothelial migration and monocyte adhesion. The study found a modulation of gene expression in cell-cell adhesion mechanisms, confirming anthocyanins' protective role in vascular health.³¹ In an oxidative stress model using HaCat keratinocyte cell lines, anthocyanins extracted from *Hibiscus syriacus* L. reduced H₂O₂-mediated apoptosis

by decreasing mitochondrial ROS production, stabilizing mitochondrial membrane potential, and activating the Nrf2 pathway, which upregulated antioxidant defence genes such as HO-1 and NQO1. This mechanism provided strong protective effects against oxidative damage in skin cells.³² A32n IL-1 β -induced oxidative stress model in Caco-2 cells demonstrated that anthocyanin-rich wild blueberry extract suppressed NF- κ B activation thereby mitigating gut inflammation and oxidative stress in intestinal epithelial cells dose dependently.³³ Blueberry anthocyanins inhibited VEGF expression, Akt pathway and upregulated SOD activity, contributing to oxidative stress reduction on high glucose- induced human retinal capillary endothelial cells.⁴¹

Cancer Cell Line Studies: Anthocyanins have also been studied in cancer models. P3G and C3G induced a dose-dependent inhibition of cellular proliferation and apoptosis in multiple cancer cell lines, demonstrating their potential as therapeutic agents.³⁴ Anthocyanins extracted from purple rice reduced inflammation by suppressing NF- κ B signaling in chondrocytes, indicating potential benefits for joint health and arthritis management.³⁵ Anthocyanins from purple tea shoots induced apoptotic fragment formation and nuclear compaction, while *L. caerulea* 'Beilei' fruit extract (100 μ g/mL) promoted G2/M phase arrest, significantly inhibiting cancer cell proliferation.^{36,37} D3G and C3G induced apoptosis in HTC cell lines. It also reduced expression of the PD-L1 protein in HCT-116 cells and the intensity of PD-L1 fluorescence by 39%.³⁹ Anthocyanins from strawberries reduced triglycerides and LDL-cholesterol and enhanced HepG2 cell redox status via modifying thiobarbituric acid-reactive compounds, antioxidant enzyme activity, and ROS formation.⁴⁰

Gut, Hepatic, and Immune Models

Additional studies have explored the broad antioxidant and anti-inflammatory effects of anthocyanins. Anthocyanins prevented Caco-2 monolayer permeabilization, NOX1/4 upregulation, oxidative stress, and NF- κ B/ERK activation caused by tumor necrosis factor alpha and Protect GI physiology in HFD-induced obesity via redox-regulated pathways.³⁸ C3G suppressed NF- κ B activation and reduced p65 nuclear translocation in macrophage cell lines, leading to reduced

inflammatory responses.⁴² C3G also downregulated pro-inflammatory proteins while upregulating anti-inflammatory markers, further validating its anti-inflammatory role.⁴³ Fermented grape and strawberry anthocyanins were shown to induce caspase-3-mediated apoptosis in colon cancer cells, supporting their potential anticancer properties.⁴⁴ A blueberry lyophilized extract significantly reduced inflammatory cell counts and regulated phospholipase C pathway gene expression, providing further evidence of anthocyanins' anti-inflammatory effects.⁴⁵ In an oxidative stress-induced hepatocyte model, anthocyanins from native Chilean berries exhibited a dose-dependent decrease in oxidative stress markers, confirming hepatoprotective effects.⁴⁷ Delphinidin significantly inhibited HCV viral envelope formation, suggesting potential antiviral applications of anthocyanins.⁴⁶ In another study in cellular models, Pelargonidin-3-O-glucoside and its metabolites showed no significant activity on oxidative stress.⁴⁸

Systemic Anti-inflammatory and Oxidative Stress Modulation

A 14-day randomized controlled trial in healthy adults demonstrated a dose-dependent decrease in 8-iso prostaglandin F $_{2\alpha}$ and IL-10 levels with anthocyanin intake of 20–320 mg/day, with significant effects observed at doses above 80 mg/day.⁴⁹ A 6–12 week randomized crossover trial in dyslipidaemia patients receiving 40–320 mg purified anthocyanins daily showed significant reductions in oxidative stress markers, including 8-OHdG, IL-6, 8-iso-PGF $_{2\alpha}$, MDA, and TNF- α .⁵¹

Cardiovascular and Metabolic Benefits

A single 5-hour dose of 320.4 mg anthocyanins significantly improved postprandial metabolism, reducing endotoxemia, glycemia, and lipidemia.⁵⁰ A 12-week study in postmenopausal women consuming 500 mg of elderberry extract daily found no significant effects on fatty acid profiles.⁵³ In a 4-week trial, 80 mg anthocyanins significantly lowered uric acid, hs-CRP, fasting blood glucose, HDL, LDL, triglycerides, and cholesterol levels.⁵⁴ Athletes taking 6 g/day of New Zealand blackcurrant powder for 7 days showed a 25% increase in cardiac output and stroke volume, with reduced plasma lactate accumulation.⁵⁵ A study on tart cherry powder (400–480 mg for 2 weeks) showed a reduction in deoxygenated hemoglobin, although heart rate remained unchanged.⁵⁶ A study in

hypertensive patients with metabolic disorders supplemented with 250 mg anthocyanins daily for 8 weeks resulted in reduced IL-6 and TNF- α levels.⁵⁸ A study in pre-hypertensive adults who consumed 640 mg of anthocyanins daily for 4 weeks observed a significant increase in HDL cholesterol.⁵⁷ Another study in sedentary postmenopausal women who

consumed 250 g of blueberries daily for 6 weeks reported improved NK cell activity, decreased arterial stiffness, and lowered diastolic blood pressure.⁶² A study in hypertensive patients (BMI >30 kg/m²) consuming 10 g of dried purple-black barberry for 8 weeks demonstrated improvements in lipid profiles and reduced CRP levels.⁶³

Table 2. Summary of antioxidant and anti-inflammatory effect of Anthocyanin on human trials

Population	Intervention with duration	Findings	Reference
Healthy Young Adults	Extracted Anthocyanins Duration of 14 days	Dose-dependent \downarrow 8-iso prostaglandin and plasma interleukin-10 F2 α .	49
Healthy Adults	Purified Anthocyanins Duration: 5h	Modulate the associated postprandial dysmetabolism, endotoxemia, alterations of glycemia and lipidaemia, and redox and insulin signalling.	50
Adults with Dyslipidaemia	Purified Anthocyanins Duration: 6 weeks and 12 weeks	Dose-response association with \downarrow 8-OHdG, IL-6, 8-iso-PGF2 α , MDA, TNF- α , and oxidative stress biomarkers	51
Older adults BMI above 30.6 kg/m ²	High-fat high-energy meal with anthocyanins-rich queen garnet plum Duration: 2 h	\downarrow CRP levels, \downarrow IL-6.	52
Post menopausal women	Elderberry extracts Duration: 12 weeks	No significant impact on fatty acid profiles and biomarkers of CVD.	53
Normal healthy and MetS (age 25-75y) male and female	Purified anthocyanins Duration: 4 weeks	Significant \downarrow Uric acid, hs-CRP, FBG, HDL, LDL, TG, Cholesterol	54
Endurance sport athlete	New Zealand blackcurrant powder Duration for 7 days	\downarrow Total peripheral resistance by 16%, improved stroke volume and cardiac output by 25% and \downarrow plasma lactate	55
Healthy Adults	Tart cherry powder. Duration: 2-week placebo control trials	No notable drop-in heart rate, and diastolic blood pressure, deoxygenated hemoglobin	56
Pre hypertensive adults	Anthocyanins Duration: 4 weeks	\uparrow HDL cholesterol production in pre-hypertensive and non-dyslipidaemia patients.	57

Adults with mild cognitive impairment	Anthocyanins extract Duration: 8 weeks	↓Serum TNF- α in senior adults. No effects noted on other inflammatory biomarkers (IL-6, hs-CRP, and IL-1 β), microcirculation function, or 24-hour ambulatory blood pressure. No effects noted in the group that received low dose of food anthocyanins.	58
Healthy age male extracts	New Zealand blackcurrant Duration: 14 days	Longer duration of intake \uparrow fatty acid oxidation and alters substrate oxidation metabolism in moderate-intensity exercises.	59
Brazilian Adults BMI between 30 and 39	Jucara freeze dried pulp Duration: 6 weeks	↓MCP-1 and IL-6 TNF- α production, \uparrow IL-10 mRNA concentration, and \downarrow pro-inflammatory condition in obesity.	60
Adult with T2DM	Anthocyanins Duration: 4 weeks	Significant \downarrow IL-18, IL-6, and TNF- α observed in T2DM group.	61
Men and postmenopausal women aged 18 to 50 years, Sedentary population.	Blueberry powder Duration: 6 weeks	\downarrow NK cells, A1x, ASP, and diastolic pressures in sedentary males and females.	62
Age group 25 – 60 yrs with a history of hypertension and obesity, on nitrate or high dosage statin medications (rosuvastatin > 20 mg/day, atorvastatin > 40 mg/day or) Duration for 8 weeks	Dried purple-black barberry along with sucrose	\downarrow Lipid profile (TC: LDL-C, HDL-C, sd-LDL-C and TG): Plasma CRP levels in the barberry group in comparison to the placebo group, and a tendency toward \downarrow plasma IL-6 levels was noted	63

Dose-Response Relationship and Optimal Duration

A meta-analysis determined that anthocyanin doses greater than 200 mg/day for 4 weeks significantly enhanced vascular function and reduced inflammatory markers, but intake beyond 500 mg/day did not proportionally increase benefits, suggesting a saturation threshold.⁵² Another study found that short-term high-dose treatments

provided better outcomes than long-term low-dose supplementation.⁵⁹ A study in obese individuals found that 5 g/day of freeze-dried Jucara pulp for 6 weeks led to increased IL-10 expression and reduced pro-inflammatory markers.⁶⁰ A study in Type 2 Diabetes Mellitus patients receiving 320 mg/day of anthocyanins for 4 weeks showed significant reductions in IL-6, IL-18, and TNF- α .⁶¹

Discussion

A harmful factor's effect causes the body to respond widely, which is known as inflammation. The factor may be mechanical, chemical, biological, or physical. Additionally, the causes may be separated into external and endogenous categories. Inflammation serves to mobilize the body, cells, and regulators that the cells create to combat and neutralize the danger. Redness, inflammation, fever, impairment of function, and discomfort are the hallmarks of inflammation.^{64,65} Cancer also can be caused by a variety of factors, including genetics (e.g., BRCA2 and BRCA1 in breast cancer), environmental exposure to oncogenic agents (e.g., tobacco smoke, asbestos, UV radiation), environmental influences (e.g., low-vegetable diet, lack of physical activity, excessive alcohol consumption, smoking), and infections (e.g., human papillomavirus HPV, hepatitis B).^{66,67} According to recent research, anthocyanins, natural plant pigments are gaining popularity because of their many health advantages, which include their ability to reduce inflammation as well as cancer. Anthocyanins may be useful in the management and avoidance of inflammation because of their potent antioxidant qualities. Thus, they show also anticancer effects.

The research revealed that the sources of anthocyanin varied. Diverse fruits and rice were used as an intervention; the fruits used were purple black barberries,⁶³ blueberries^{33,41,45,62} jucara pulp,⁶⁰ black currant extracts,^{55,59} chilean berries,⁴⁷ fermented strawberry and grape,⁴⁴ tart cherry,⁵⁶ elderberry,⁵³ and queen garnet plum⁵² and the rice are black rice and purple rice.^{34-35,42} Certain studies also made use of purified anthocyanins. Among the studies, monomeric anthocyanin components were used, including pelargonidin-3-O-glucoside, D3G, and C3G.^{44,46,48} Orally administered anthocyanins in the form of supplementation and/or by addition to diet or related to the intake of food included in the mentioned studies anthocyanin intervention ranges widely from 1 week to 8 weeks.⁴⁹⁻⁵¹

Among all the study publications, some investigated a decrease in ROS activity^{35,45}; moreover, studies on cancerous cells revealed that anthocyanin intervention had beneficial effects. Some studies showed the stimulation of cellular redox pathways and investigations in which anthocyanin intervention had no meaningful effects.⁴⁸ Research including all

research indicated that Nrf2 decreased the formation of ROS.^{40,41} This includes research that observed an elevation in catalase activity,⁴⁰ an enhancement in SOD activity,⁴¹ encourage EC proliferation, a key step in angiogenesis and wound healing⁴⁵ and a study that noted an increase in caspase activity.⁴⁴ One study indicated an increase in HDL cholesterol among pre-hypertensive and non-lipidemic individuals, an enhancement in fatty acid oxidation during moderate-intensity exercise, and an increase in interleukin-10 mRNA concentration.⁵⁷ Dose dependent result observed in clinical trials. Dietary intake of anthocyanin extracts showed dose-dependent decrease in 8-iso prostaglandin F2 α and IL-10 levels and significant reductions in oxidative stress markers.^{49,51,58} Dosage 300-320 mg anthocyanin extracts showed optimal results^{47,49,51,54,61}; A dose-dependent relation was witnessed higher doses are more effective in short duration.^{54,55}

The findings of the studies under consideration demonstrate how anthocyanin extracts have anti-inflammatory and antioxidant properties when applied to cell cultures. In one study, anthocyanin extracts were shown to modify gene expression associated with cell-cell adhesion by drastically reducing monocyte adherence and trans endothelial migration in endothelial cells exposed to TNF- α .³¹ Another study on HaCat keratinocyte cell lines demonstrated that anthocyanin extracts from *Hibiscus syriacus* L. alleviated oxidative stress-induced apoptosis by stabilising mitochondrial membrane potential and decreasing ROS production.³² Furthermore, anthocyanins activated the Nrf2 pathway, initiating antioxidant defence mechanisms, thereby reinforcing their protective function against inflammation and oxidative stress.³² The findings indicate that anthocyanins, regardless of dosage and duration, produce beneficial effects via multiple cellular pathways, highlighting their potential for therapeutic applications. Additional research is required to establish the maximum level of anthocyanin consumption for achieving optimal health benefits while maintaining safety. Metabolic variability among individuals, as a function of genetic polymorphisms and gut microbiota, can potentially be important in establishing dosage recommendations for optimal effects. The interaction of anthocyanins with food components and their sustained effects over the long term need to be factored into future intervention studies.

Conclusion

This narrative review evaluates the effects of anthocyanins in the form of extracts or association with other foods and their impact as antioxidant and anti-inflammatory component. Therefore, this narrative review verifies that anthocyanins from different food sources improve inflammatory parameters. This study addresses the crucial function of anthocyanins in regulating inflammatory and oxidative stress pathways, demonstrating their potential therapeutic benefits in chronic diseases. The findings demonstrate that anthocyanin supplementation substantially reduces pro-inflammatory cytokines, like IL-1 and IL-6 while increasing anti-inflammatory markers like Interleukin-10. The review also emphasizes how the bioactivity of anthocyanins is dose-dependent, with greater impacts being generated by larger quantities given for a shorter period. Mechanistic discoveries show that anthocyanins have anti-cancer capabilities because they affect the manifestation of genes associated with endothelial function and cellular adhesion. In addition, anthocyanins are further demonstrated as potent antioxidants with immunomodulatory potential by regulating the generation of mitochondrial ROS and stimulating Nrf2. Therefore, the research offers strong evidence in favour of including dietary interventions high in anthocyanins to reduce oxidative stress and inflammation-related illnesses.

However, present data firmly supports anthocyanins' anti-inflammatory and anti-cancer characteristics. Further study is required to completely understand the mechanisms of action and optimize anthocyanins usage for the prevention of inflammation including cancer.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

Even though adequate data has been given in the form of tables and figures, however, all authors declare that if more data required then the data will be provided on request basis.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration

This research does not involve any clinical trials.

Permission to Reproduce Material from other Sources

Not applicable

Author Contributions

- **Anindita Ghosh:** Conceptualization, Methodology, Writing-original draft
- **Sunanda Biswas:** Visualization, Supervision, Writing – Review & Editing
- **Sneha De:** Methodology, Writing-original draft
- **Samyak Ingale:** Methodology, Data collection, Analysis, Writing-original draft

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