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Review Article

A Review of Tannin Compounds in Avocado as Antioxidants

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ABSTRACT

Avocados, a fruit from *Persea americana*, are highly nutritious and energy-dense. However, some people eat the tasty fruit and rarely use other plant parts that can benefit their health. Rarely used plant parts like seeds, leaves, and fruit peels are known to contain active secondary metabolites, including tannin. Tannins are polyphenolic chemicals with antioxidant properties. Antioxidants can protect against oxidation reactions induced by reactive species like hydrogen peroxide, hydroxyl radicals, and superoxide anion radicals. These reactive organisms can cause a variety of degenerative illnesses in humans. The study aimed to identify the potential of tannin compounds in avocado trees as antioxidants that may benefit human health. The literature review was conducted by searching national and international scientific journals using Science Direct, Google Scholar, and PubMed search engines. Tannins demonstrate antioxidant action by reducing free radicals, chelating transition metals, and inhibiting pro-oxidative enzymes. Condensed tannin molecules such as catechins, epicatechins, procyanidins, and proanthocyanidins were considered responsible for avocados' antioxidant action. Further investigation into the potential health benefits of avocado tannins through a multidisciplinary approach, including biochemical characterisation, bioavailability studies, and clinical investigations, is recommended.

***Keywords*:** Avocado, Antioxidants, Procyanidin, Tannins.

Introduction

Avocados (*Persea americana*) are plants from Central America and southern Mexico.[1] This plant, which comes from the Lauraceae tribe, has fruit that is rich in energy sources and is one of the fruits with excellent nutrition because it contains large amounts of fat, protein, and fibre. Avocados are also rich sources of vitamins (vitamins C, E, K, B1, B2, B6, and B9) and minerals (phosphorus, sodium, magnesium, potassium, iron, and zinc). Therefore, avocados have the potential to improve health and cure diseases.[2]Most people only eat the fruit and hardly ever use the other parts of the plant. Traditionally, an avocado leaf decoction can lower blood pressure.[3] Many studies have reported that avocado seed and leaf extracts have antiviral activity,[4] anti-diabetic activity,[5] antimicrobial activity, and antioxidant activity.[6] Recent studies have shown that avocado seeds have anti-inflammatory and anticancer properties.[7] Avocado seeds and their skin are rich in polyphenols with antioxidant and antibacterial properties.[7] Polyphenols are widely recognised for their antioxidant activity, which works by preventing lipid peroxidation due to free radical attacks. The food industry can use these compounds as a preservative to increase their products's shelf life.[8] Industries are interested in these polyphenols because they are antioxidants. These compounds can stop lipid peroxidation and scavenge reactive species like hydrogen peroxide, hydroxyl radicals, and superoxide anion radicals.[9] In humans, these compounds can protect against direct or indirect oxidation caused by metal cations.[10]

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These cations are harmful to humans because they can stimulate the formation of ROS (reactive oxygen species).[8] ROS is a free radical formed as a byproduct of oxidative metabolism. It is highly reactive and can propagate a chain reaction that forms more free radicals.[12] ROS can cause oxidative stress that can be associated with various pathologies, including neurodegenerative activity, cardiovascular disease, cancer, and aging.[11]

There are different methods to extract, characterise and identify tannins from avocados: solvent extraction, solid-liquid extraction, enzyme-assisted extraction, solid-phase extraction (SPE), high-performance liquid chromatography (HPLC) and nuclear magnetic resonance (NMR) spectroscopy.[12] These methods capture a spectrum of tannin compounds with varying chemical properties, allowing for precise identification and quantification. Enzyme-assisted extraction uses enzymes to break down cell walls, while solid-phase extraction uses resins or sorbents for targeted isolation. HPLC allows for precise identification and quantification of tannins, while NMR spectroscopy validates the identity of isolated compounds.[13]

Antioxidants are substances that can delay, slow down, or prevent oxidation and are very useful in neutralising free radicals and preventing damage to macromolecules. Antioxidants work in several ways: metal particle complexation, free radical scavenging, and peroxide decomposition.[14] Many studies have reported the discovery of antioxidant compounds in plants' seeds, leaves, fruits, and fruit skins. Several natural compounds found in plants are thought to have antioxidant activity, namely phenolic compounds, flavonoids, and tannins.[15]

Animals and humans cannot synthesise tannins, which are vegetable polyphenols. Plants widely distribute them as protective substances against harmful external influences. Therefore, animals and humans depend on the exogenous supply of these plant-based antioxidants.[16] According to their structural characteristics, both types have different activities. The complex structure of condensed tannins prevents absorption and possesses binding properties that can cause local effects on the digestive tract. These tannins can have antioxidant, antimicrobial, antiviral, antimutagenic, and antinutritional properties. On the other hand, hydrolysed tannins are absorbable because of their low molecular weight. The metabolites absorbed from tannin

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fermentation in the colon can produce systemic effects in various organs.

Avocado tannins, rich in polymeric structures with phenolic hydroxyl groups, have medicinal properties in ethnomedicine, providing anti-inflammatory, antimicrobial, and antioxidant effects.[17] These compounds, besides ethnomedicine uses, have potential applications in food preservation, pharmaceuticals, and functional foods, contributing to preventive medicine and nutraceuticals. In recent years, studying natural sources of potent antioxidants has garnered considerable interest in nutrition and health. People have recognised avocado, a fruit renowned for its abundant nutritional content, as a possible source of distinctive bioactive chemicals, specifically tannins. While a wide range of plant species frequently link to tannins, their precise presence and function in avocados remain largely unknown. Hence, further scientific inquiry is warranted about the antioxidant properties of tannins found in avocado trees. This literature study assessed the potential of tannins found in avocado plants and their function as antioxidants with possible human health benefits. It presents new insights into the potential uses of avocados as a natural antioxidant source, which may have significant implications for human health and overall well-being.

The methodologies used in this research are critical for elucidating the complexities of tannin compounds found in avocados and providing evidence for our investigation's originality. This study aims to comprehensively analyse the structural variability of tannin compounds found in avocados through thorough literature searches, systematic data extraction methods, and detailed analyses. This investigation seeks to clarify the antioxidative characteristics of these compounds as well as any potential health-related implications they may have.

The review methods also include a complete analysis of all the experiments that have been done, improvements made to analytical methods, and progress made in isolating and characterising tannin compounds that come from avocados. The study employs rigorous review methodologies to ensure the reliability of its results and detect deficiencies in previous studies. This approach strengthens the study's credibility and contributes to advancing knowledge about antioxidants in avocados, strengthening its influence in the scientific community.

Materials and Method

The review methods utilised in this research are intentionally structured to thoroughly evaluate and amalgamate the current body of knowledge regarding tannin chemicals in avocados. This guarantees a thorough and reliable investigation of the topic. The assessment of methodologies took into account many crucial parameters to ensure the dependability and pertinence of the results.

Strategy for literature search

An extensive and systematic literature review encompassed many databases (e.g., Web of Science, Scopus, and PubMed),[18] using pertinent terms such as 'avocado,' 'tannin compounds,' and 'antioxidant.'. Predetermined inclusion and exclusion criteria were implemented to guarantee the inclusion of research relevant to the review's aims.

Extraction and synthesis of data

A comprehensive data extraction procedure was utilised to collect information about the diverse tannin compounds found in avocados, encompassing their chemical compositions, origins, and purported bioactivities. Synthesizing data entailed classifying and synthesising discoveries to construct a logical and consistent narrative.

Evaluation of included studies for quality

An exhaustive quality evaluation was conducted for each selected study, adhering to predetermined criteria. Assessing the dependability of the data retrieved from individual research required examining the experimental design, methodological rigour, and reporting transparency.

Analysis of structural diversity

A comprehensive chemical structure investigation was performed to elaborate on the structural diversity of tannin compounds found in avocados. This process entailed classifying tannins into several classes and clarifying their molecular structure changes, enhancing our comprehension of their multifaceted nature.

Evaluation of antioxidative properties

The review methodology included a critical evaluation of the purported antioxidative activities of avocado tannin components. The examination will focus on the processes underlying antioxidant activity and the possible health consequences.

Ethnomedicinal and additional uses investigation

In pursuit of ethnomedical and other applications, avocado tannin components were subjected to an exhaustive examination of their traditional and modern usage. An extensive evaluation was conducted on pertinent studies that emphasised the medicinal or bioactive properties and prospective applications beyond traditional medicine.

Determination of study gaps

The review employed methodologies designed to identify deficiencies in the current body of literature, thereby guiding potential avenues of future research. By identifying specific domains that require additional inquiry, the review actively contributes to the continuous progression of understanding on this particular topic.

Through strict adherence to these predetermined criteria, the review techniques guarantee a thorough, transparent, and resilient examination of the tannin compounds present in avocados. By employing this methodology, the synthesised data is more dependable and furnishes a significant asset for scholars and professionals intrigued by the multifaceted aspects of tannins generated from avocados.

Results and Discussion

This review's primary focus was on uncovering the variety of antioxidant qualities inherent in the tannin-based compounds found in avocados. Due to its enormous implications for human health and nutrition, the antioxidant capacity of these substances has emerged as a primary area of attention.

Avocados contain good nutrition and do not contain cholesterol (Table 1).[19] The body needs cholesterol, but excessive amounts can cause atherosclerosis, which can cause hypertension and block blood vessels. Generally, an organism's fat serves many functions, including insulation and maintaining body temperature in living things. Diets often substitute protein for carbohydrates. As a chemical compound, proteins repair and replace old cells, form structural and globular proteins that can defend the body, create blood proteins, and boost the immune system. Avocados have a high carbohydrate content, which contributes to energy production. Fibre may alter the colon's environment to help prevent colorectal disease. A high-fat diet can increase colonic bile acid concentrations, but fibre can reduce colonic bile acid growth by increasing faecal bulk. In an organism's body, an increase in fibre content can reduce the occurrence of diseases such as diabetes, hypertension, haemorrhoids, and digestive disorders.[20] Mineral elements have beneficial effects on an organism's body, and most of them are in the form of a solution, allowing them to diffuse to other parts of the plant. Sodium and hypertension are closely related.[21] Excessive sodium content can lead to an increase in blood pressure. Additionally, the presence of potassium can maintain electrolyte balance and control high pressure. Avocados can help reduce hypertension because potassium is the most abundant mineral in avocados; therefore, avocados can help reduce hypertension. According to epidemiological studies, hypertension is more prevalent in people with low potassium intake. Hypertension is a major cause of morbidity and mortality in cardiovascular disease.[22] Avocados are rich in calcium, aiding bone formation and blood clotting.[23]

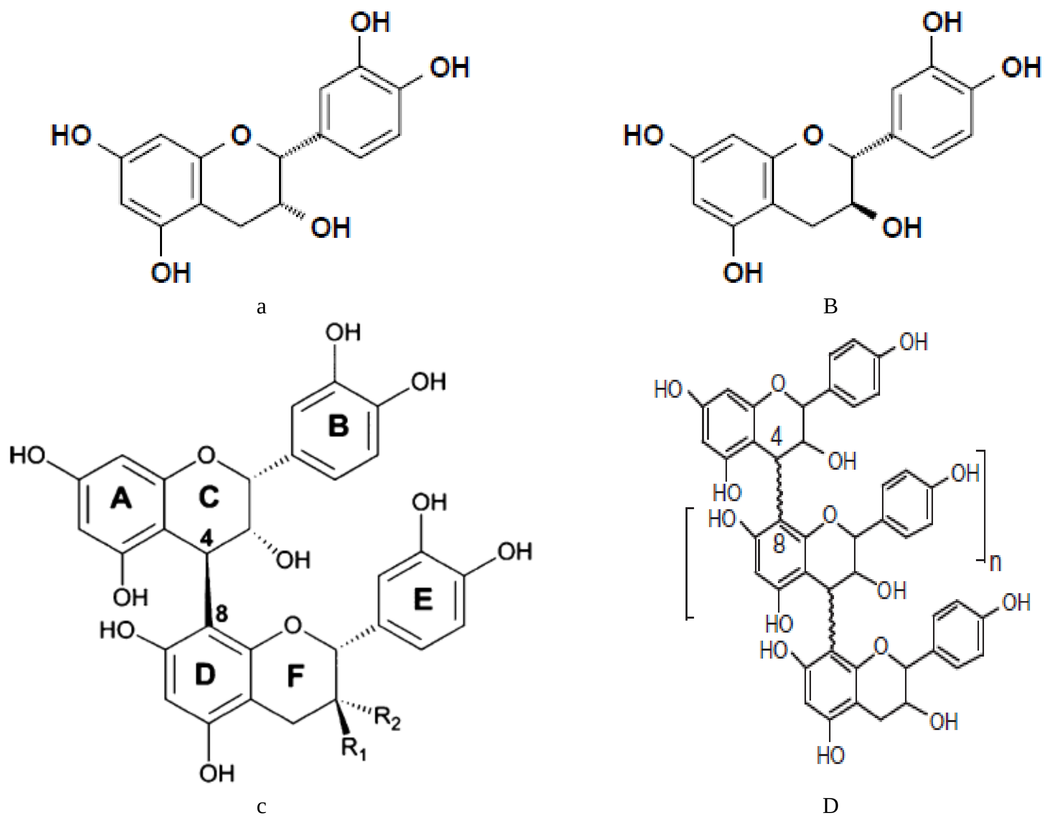

Figure 1: The structure of condensed tannin compounds.
(a) Epicatechin, (b) Catechin, (c) Procyanidin, and (d) Proanthocyanidin.[14]

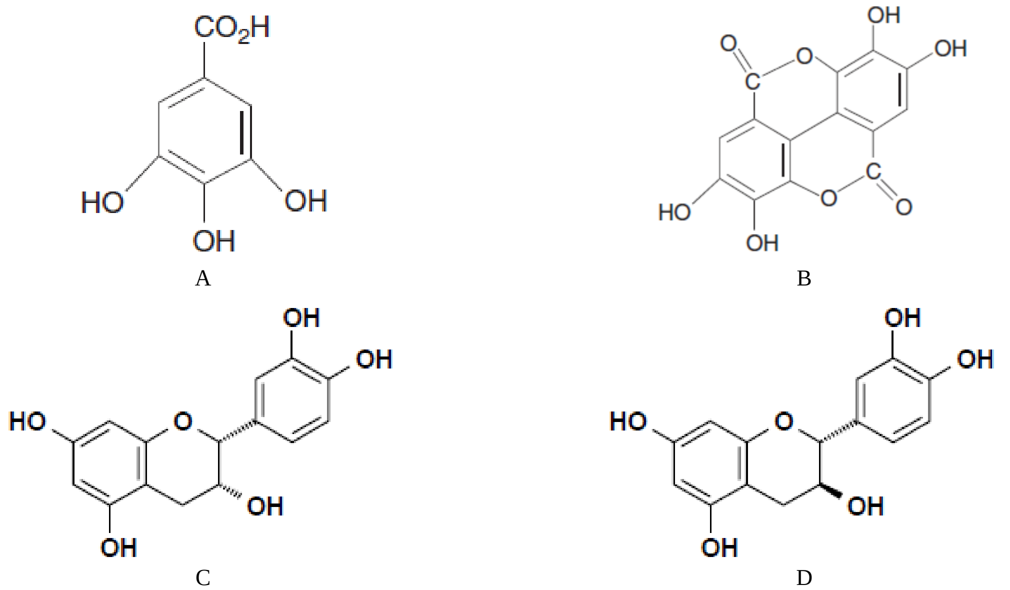

Figure 2: Structure of tannin compounds.
(a) Gallic acid and (b) Ellagic acid - Hydrolysed tannins; (c) Epicatechin and (d) catechin-condensed tannins.[24]

Content of secondary metabolites in avocado plants

Avocados contain several secondary metabolites scattered throughout various parts of the plant (Table 2). Primary metabolites, such as carbohydrates, proteins, and fats, play a crucial role in the body of an organism, contributing to growth and development. Meanwhile, secondary metabolites serve a defensive role in plants. Furthermore, reports suggest that secondary metabolites contain health-promoting bioactive compounds. Saponins are glycosides that produce foamy solutions exhibit hemolytic properties, and are toxic to fish and shellfish.[25] Reports suggest that some plant-derived saponins can lower plasma cholesterol levels.[26,27] Alkaloids have been reported to have antibacterial and antifungal activities.[28] Tannins exhibit astringent properties, anti-diarrheal effects, antibacterial action, and antioxidant activity.[29] Pharmacological studies on these secondary metabolites have demonstrated their importance for health.

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Table 1: The nutritional composition of avocados in a 100-gram portion[30]

Nutrition Composition	Amount	Nutrition Composition	Amount
Water	72.23 g	Riboflavin	0.13 mg
Energy	160 kcal	Niacin	1,738 mg
Proteins	2 g	Vitamin B6	0.257 mg
Total fat	14.66 g	Total folate	81 µg
Carbohydrate	8.53 g	Total choline	14.2 mg
Fiber	6.7 g	Vitamin A, RAE	7 µg
Total sugar	0.66 g	*β*-carotene	62 µg
Calcium	12 mg	*α*-carotene	24 µg
Iron	0.55 mg	*β*-cryptoxanthin	28 µg
Magnesium	29 mg	Lutein + zeaxanthin	271 µg
Phosphor	52 mg	*α*-tocopherol (vitamin E)	2.07 µg
Potassium	485 mg	Vitamin K	21 µg
Sodium	7 mg	Total saturated fatty acids	2.126 g
Zinc	0.64 mg	Total monounsaturated fatty acids	9.799 g
Copper	0.19 mg	Total saturated fatty acids	2.126 g
Selenium	0.4 µg	Total monounsaturated fatty acids	9.799 g
Vitamin C	10 mg	Total polyunsaturated fatty acids	1.816 g
Thiamin	0.067 mg	Cholesterol	0 g

Table 2: Content of secondary metabolites in avocado plants

Plant Part	Content
Seed[31]	Saponins, tannins, flavonoids, alkaloids, and Steroids.
Leaf[32]	Flavonoids, saponins, tannins, and steroids.
Fruit[31]	Saponins, tannins, flavonoids, alkaloids, and steroids.

Compounds in the avocado plant with potential antioxidant properties

Tannins are among the compounds with the potential to act as antioxidants in avocado plants (Fig. 2). Tannins can be categorised into two types: hydrolysed tannins and condensed tannins. Hydrolysed tannins consist of gallic acid and hexahydroxydiphenic acid polyesters (gallotannins and ellagitannins). Meanwhile, condensed tannins comprise oligomers of polymers composed of flavan-3-ol, better known as proanthocyanidins (Fig. 3).[33] Table 3 details the compounds in avocado plants that can act as antioxidants. Condensed tannin compounds, such as procyanidins, epicatechins, catechins, and proanthocyanidins (Fig. 1) found in avocado plants, have the potential to act as antioxidants.

The majority of compounds are condensed tannins (Table 3). The chemical activity of condensed tannins is determined by the molecular properties of rings A and B (Fig. 1).[34] Ring A is responsible for the stability of the interflavonoid bond and acts as an adhesive, while ring B determines the properties of metal complex formation and the antioxidant characteristics of tannins.

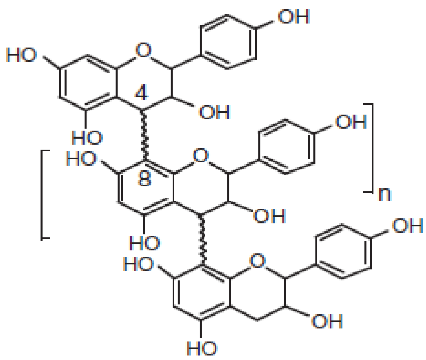

Figure 3: Proanthocyanidin structure.[35]

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Table 3: Compounds in avocados have the potential as antioxidants

Varieties, Plant Parts	Extract Type	Method	Compound
Hass and Skin[36]	50% (v/v) ethanol extract	HPLC combined with QTOF	Procyanidins, flavonols, hydroxybenzoate, and hydroxamic acid.
Hass, Seeds, and Seed Coats[37]	Accelerated solvent extraction	HPLC-DAD-ESI-QTOF-MS	Condensed tannins, phenolic acids, and flavonoids.
Hass and Seeds[8]	Methanol and ethanol extract 50% (v/v)	HPLC, ABTS, FRAP, ORAC, and EPR	Chlorogenic acid, epicatechin, catechin, and procyanidin.
Hass, Skin, and Seeds[38]	Water extract	ORAC	Epicatechin and chlorogenic acid.
Hass and Fuerte, Husks, and Seeds[39]	80% (v/v) ethanol extract by ultrasonic extraction	ABTS, DPPH, FRAP and HPLC-ABTS	Skin: Procyanidin B2 and epicatechin. Seeds: trans-5-O-caffeoyl-D-quinic acid, procyanidin B1, catechins, and epicatechins.
Hass and Shepard, Seeds, and Skins[40]	Methanol extract 80% (v/v)	HPLC-PAD, HPLC-ESI-MS, DPPH, ABTS, and ORAC	The monomers of flavanols, proanthocyanidins, and hydroxamic acid
Hass, Fruit Flesh[41]	Methanol extract	UHPLC-HE-MS	Gallic acid, sinapinic acid, vanillin, p-coumarin acid, gentisic acid, strong proteacate acid, 4-hydroxybenzoic acid, chlorogenic acid, and benzoic acid.
Hass, Hass, Fruit[42]	Methanol extract	GC coupled with APCI-TOF MS and FID	Quinic, ferulic, chlorogenic, and p-coumarin acids, epicatechins, and quercetin.
Mexican Landrace, Leather[43]	Methanol extract	DPPH	Activity can be attributed to anthocyanins.
The Flesh of the Fruit, Skin, and Seeds[44]	Extract acetone, water, and acetic acid	HPLC-MS, ORAC, and DPPH	Catechins, epicatechins, A- and B-type dimers, A- and B-type trimers, pentamers, and hexamers have been identified in the shells and seeds.

The tannin content in avocado plant parts

The content of compounds in plants varies due to several factors, such as variety, plant parts used, simple processing, the extraction process, and the origin of the plant. Similarly, the tannin content of avocado plants is detailed in Table 4. The avocado seed contains the highest concentration of tannins among the plant parts. The concentration of tannin compounds in extracts plays a crucial role in determining the antioxidant activity of plant extracts. Various factors, including the drying process and extraction conditions, can influence the concentration and stability of these compounds.

The content of tannin compounds in different plant parts varies due to treatment differences during extraction. High temperatures and inefficient extraction methods may lead to a reduction in compound content.[45] Storage conditions, such as temperature, pH, and the use of solvents, significantly impact compound stability. Chemical modifications like hydrolysis and oxidation can occur over time, potentially reducing compound content if the extract is stored for an extended period.[46] Therefore, it is crucial to assess the stability and potential applications of the extract through *in vitro*, *in vivo*, or *in silico* methods [27,47,48], as these compounds could serve as a source of natural antioxidants. Other factors such as varieties, plant parts used, and different plant origins can contribute to variations. This review explores the potential antioxidant content of tannin compounds in avocado plants. According to Bate-Smith (1957), tannins are polyphenolic compounds with large molecular weights between 500 and 3000 daltons, making them unabsorbable. Due to their substantial molecular weight and high hydroxylation of aromatic rings, tannins are reported to demonstrate high antioxidant potential.

Tannins have a similar electrochemical redox potential to phenols. The antioxidant activity of phenols may stem from their favourable redox potential, capacity to form stable radicals, or ability to chelate metal ions. Tannins, especially at pH 6–8, exhibit a redox potential below 1,000 mV and are considered reducing agents for peroxyl and hydroxyl radicals.[49]

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Table 4: The content of tannins in avocado plant parts

Plant Part	Tannin Content	Plant Types and Conditions	Plant Origin
Leaf	0.68±0.06 mg/100g	Dried simplicia[31]	Imo State University School of Agriculture, Owerri, Nigeria.
Fruit	0.12±0.03 mg/100g	Early ripening, dried simplicia[31]	
Seed	0.24±0.12 mg/100g	Dried simplicia[31]	New Market, Enugu, Nigeria
	6.98±0.04 mg/100g	Dried simplicia[50]	
	0.36±0.04 mg/100g	Extract[51]	Oba, Idemili - southern local government territory, Anambra state, Nigeria
	117 mg/kg	Round red, Extract from dried simplicia[52]	Plantation village of Maubi Minahasa, North Sulawesi
	112 mg/kg	Avocado butter, extracted from dried simplicia[52]	
	41.333 mg/kg	Round red, Extract from fresh simplicia[52]	
	41 mg/kg	Avocado butter, extracted from fresh simplicia[52]	
	11.29±0.11 g/100g	Dry simplicia[53]	
	8.44±0.11 g/100g	Boiled at 100°C for 10' and then made into dry simplicia[53]	
	7.89±0.00 g/100g	Boiled at 100°C for 15' then made into dry simplicia[53]	
	5.37±0.11 g/100g	Boiled at 100°C for 20' then made dry simplicia[53]	
	2.74±0.11 g/100g	Boiled at 100°C for 25' then made dry simplicia[53]	
	3.60±0.11 g/100g	Maceration with water for 24 hours[53]	

Mechanisms of Antioxidant Action

Multiple mechanisms contribute to the antioxidant properties of substances derived from avocado tannin, which safeguard cells and tissues against oxidative stress. These processes ultimately mitigate the detrimental consequences of oxidative stress through their interactions with reactive oxygen species (ROS) and other oxidative molecules.[54] The phenolic hydroxyl groups in avocado tannins function as highly effective electron donors. By donating electrons, they can neutralise free radicals and prevent the formation and spread of oxidative chain reactions. Free radical scavenging prevents oxidative damage to biomolecules such as DNA, lipids, and proteins, thereby preserving cellular integrity.

Avocado tannins can chelate metal ions, specifically transition metals such as copper and iron.[55] Metal ions can catalyse Fenton reactions, producing extremely reactive free radicals. Avocado tannins employ chelation of these ions to prevent the formation of further free radicals, hence enhancing antioxidant protection.

Using hydrogen atom transfer processes, avocado tannins can neutralise free radicals.[56] Tanning compounds accomplish this by donating hydrogen atoms to free radicals, stabilising them, and impeding more cellular damage. This pathway is especially important in lipid-rich biological settings, where lipid peroxidation frequently results from oxidative stress. Certain chemicals derived from tannin can potentially impact cellular signalling pathways implicated in oxidative stress responses. Avocado tannins can modulate these pathways, influencing the expression of proteins and antioxidant enzymes crucial for maintaining cellular redox balance.[57] Avocado tannins may stimulate the activity of endogenous antioxidant enzymes such as glutathione peroxidase, superoxide dismutase, and catalase. These tannins strengthen the cellular antioxidant defence mechanism, augmenting the overall cellular resistance to oxidative damage.

Comparative analysis with other antioxidants

A comparative examination of the antioxidant activities of avocado tannins with other widely recognised antioxidants, such as vitamin C, vitamin E, and polyphenols, unveils the distinctive characteristics and possible synergistic effects among these compounds. Water-soluble antioxidant vitamin C is renowned for its capacity to counteract the harmful effects of free radicals in aqueous surroundings.[58] The phenolic hydroxyl groups included in avocado tannins enhance the antioxidant properties of vitamin C, which operates predominantly in the aqueous regions of cells. Combining these antioxidants allows a broader range of defense mechanisms to be effectively protected against lipid-soluble and water-soluble free radicals.

As a fat-soluble antioxidant, vitamin E prevents lipid peroxidation of cell membranes.[59] The antioxidant properties of avocado tannins, which

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can eliminate lipid-soluble free radicals, collaborate with vitamin E to protect cellular membranes. This partnership amplifies the antioxidant defense by treating oxidative stress in lipid-rich cellular contexts.

Numerous plant-based meals, including polyphenols, are renowned for their varied antioxidant qualities. The antioxidant capacity of avocados is enhanced by their polyphenolic content, which includes tannins, which aid in the fight against oxidative stress. The antioxidant processes of avocado tannins are complemented by the structural diversity of polyphenols, which includes stilbenes and flavonoids, providing synergistic and comprehensive protection against free radicals. Synergistic effects may occur when avocado tannins are combined with other antioxidants, resulting in a combined antioxidant capacity that surpasses the sum of the individual contributions. Potential synergy among these antioxidants could be facilitated by complementary mechanisms, such as reciprocal regeneration following the neutralisation of reactive species or the scavenging of distinct free radicals.

Similar to other polyphenols, the bioavailability of avocado tannins may differ in comparison to that of vitamins C and E.[60] It is imperative to comprehend the mechanisms underlying the absorption, distribution, metabolism, and excretion of these substances to evaluate their overall efficacy *in vivo*. The comparative antioxidant activity and possible health advantages of avocado tannins may be hampered by their bioavailability.

An examination of avocado tannins in comparison to widely recognised antioxidants highlights the possible synergistic effects and complementing functions that these compounds may have on cellular defence processes. The collaborative effects of avocado tannins with other antioxidants and their distinctive structural characteristics lead to their importance as a natural source of multimodal antioxidant defence.

Implications for human health

Avocado tannin components possess antioxidant qualities that may provide several possible health advantages, with a particular emphasis on mitigating illnesses associated with oxidative stress. Bioactive substances play a role in cellular defence systems and could benefit diverse facets of health. Hagerman *et al.* (1998)[37] emphasised that tannins are phytochemical compounds worthy of consideration as disease prevention agents (Fig. 2). The antioxidant activity of tannins relies on their chemical structure and the physicochemical environment (e.g., pH, redox potential, and oxidation concentration).[61] Tannins with distinct structures generally exhibit different bioavailability and chemical and biological properties.

Using the deoxyribose method, Hagerman *et al*.[37] noted that redox reactions with iron can interfere with antioxidant reactivity, limiting the usefulness of this method to phenolics. However, *in vitro*, some tannins do not act as pro-oxidants. They then sought to understand the oxidative chemical properties of tannins. Their research, employing *in vitro* methods, demonstrated that tannins are highly effective antioxidants under physiological conditions.

Numerous analytical methods can be utilised to determine total antioxidants, making identifying a universally accepted method challenging. Among them are the ORAC (oxygen-radical absorbance capacity) method,[62] the metmyoglobin method,[63] and the FRAP (Ferric Reducing Ability of Plasma) method,[64] each providing a slightly different perspective. The potential interference of tannins should be considered, as they can disrupt the operation of these methods. For instance, the intrinsic fluorescence of tannins can interfere with the ORAC method, and the tendency of tannins to form complexes with iron and proteins can affect the FRAP and methemoglobin methods, respectively. However, this challenge can be overcome by measuring antioxidants specifically to assess both the overall potential effectiveness of antioxidants and the level of oxidative and pro-oxidant damage.

Tannins can play a role in complex antioxidant defence systems. According to Koleckar et al. (2008), the fundamental mechanisms of the antioxidant activity of tannins include free radical scavenging, transition metal chelation, inhibition of pro-oxidative enzymes, and lipid peroxidation. The concept of free radical scavenging activity involves the ability of antioxidants to donate electrons to free radicals, resulting in a stable structure. The reducing activity increases with the number of hydroxyls, especially in the ortho position on the benzene nucleus. The antioxidant activity is also influenced by molecular size; generally, this applies to proanthocyanidins. However, the activity of type B procyanidins showed ambiguous results due to differences between the results of various studies (Fig. 3).[65]

Transition metals such as iron and copper are essential in the human body as cofactors for antioxidant enzymes like superoxide dismutase, catalase, and glutathione peroxidase. These transition metals are typically bound to proteins such as ferritin and ceruloplasmin.[66] The Fenton reaction is a typical and well-known example of this reaction.[67] Studies on the antioxidant activity of tannins found that tannic acid was more efficient in protecting against 2-deoxyribose degradation than the classical scavenging of hydroxyl radicals.[68] Other studies suggest that the high antioxidant activity of procyanidin is due to iron chelation and the resulting inhibition.[69] In another study related to the stability of the aluminum-proanthocyanidin complex, it was concluded that the stability of the complex increases in direct proportion to the degree of polymerisation, and the presence of phenolic groups, especially in ring B with the ortho position, is an essential parameter for chelation activity.[70]

Tannins can also exhibit antioxidant activity by inhibiting pro-oxidative enzymes and reducing nitric oxide (NO) formation by inhibiting its synthesis. Other research has found that among several tannin compounds, procyanidin B2 is the most active against NO.[71] Lipid peroxidation is involved in the oxidative modification of low-density lipoprotein (LDL), leading to atherosclerotic lesions.[72] It was reported that tannins can inhibit lipid peroxidation and have the ability to scavenge free radicals *in vitro*. Tannin activity largely depends on the chemical structure and degree of polymerisation.[73] *In vitro* studies report that catechins and their oligomers can inhibit LDL oxidation in humans, concluding that some tannins can protect LDL against oxidation.[74]

Future perspectives and research directions

The prospective developments and possible directions for more investigation into avocado tannins offer promising prospects to broaden our comprehension and fully exploit the capabilities of these bioactive substances. Advancements in extraction techniques can potentially augment the sustainability and efficacy of avocado tannin procurement. Scholars can investigate novel methodologies, including environmentally sustainable solvent-based green extraction techniques, cutting-edge technologies such as ultrasound or microwave-assisted extraction, and integrating nascent processes like supercritical fluid extraction.

Exploring the potential synergy between avocado tannins and other bioactive compounds derived from avocados or complementary plant sources is an up-and-coming field of study. Investigating how these substances interact and increase one another's antioxidant properties may result in synergistic formulations that offer improved health advantages. It is essential to evaluate the bioavailability of avocado tannins to comprehend their dispersion, excretion, metabolism, and absorption inside the human body. Further investigation may utilise sophisticated analytical methodologies, such as metabolomics, to monitor the *in vivo* trajectory of tannins. Acquiring this knowledge is critical to developing strategies that optimise these drugs' bioavailability and improve their therapeutic efficacy.

The next crucial step is conducting well-designed clinical trials to examine the health effects of avocado tannin consumption. This encompasses investigating their impact on neurodegenerative illnesses, cardiovascular health, oxidative stress-related ailments, and inflammation. Consistent clinical investigations will yield empirically supported conclusions regarding the potential health advantages of avocado tannins.

Practical ramifications abound in formulating functional foods and nutraceuticals using insights gleaned from research on avocado tannins. Producing consumable items fortified with avocado tannins while maintaining optimal flavor and stability could offer consumers a convenient way to consume these beneficial bioactive elements. The avocado is a diverse fruit, characterised by strains that differ in flavor, consistency, and dietary value. Examining the heterogeneity of tannin profiles across several avocado cultivars may reveal discrepancies in

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their antioxidant capabilities. Agricultural strategies or breeding initiatives that aim to maximise the nutritional value of avocados may be influenced by this investigation. A more thorough investigation of the cellular and molecular mechanisms that govern the antioxidant properties of avocado tannins will yield more comprehensive knowledge. Ascertaining how avocado tannins impact cellular responses to oxidative stress entails investigating signal transduction pathways, gene expression patterns, and interactions with cellular components. Scientists can make valuable contributions to the body of knowledge regarding avocado tannins and their prospective health and wellness uses by investigating these study avenues. By integrating principles from chemistry, nutrition, medicine, and food science, this research exhibits the potential of harnessing the antioxidant properties of avocado tannins into concrete health advantages that can be observed and experienced by populations and individuals across the globe.

Conclusions

This review indicates that tannins can chelate transition metals, block pro-oxidative enzymes, and reduce free radicals to demonstrate antioxidant activity. Numerous condensed tannin components, including procyanidins, epicatechins, proanthocyanidins, and catechins, have been found in avocados by scientific investigations. Thus, it may be concluded that avocado seeds' tannin constituents have great promise for use as antioxidants. This research presents challenges in avocado tannin studies, paving the way for future studies. Prospects lie in overcoming obstacles, embracing innovation, and exploring avocado tannins' potential as natural antioxidants with health benefits.

Conflict of Interests

The authors declare no conflict of interest.

Authors' Declaration

The authors of this article say that the ideas and work in it are their own and that they will be responsible for any claims that come up because of this article.

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