Meat and Muscle Biology™

Bioactive Compounds in Meat: Their Roles in Modulating Palatability and Nutritional Value

Gauri Jairath[1], Ashim Kumar Biswas[2]*, Gorakh Mal[1], and S. P. Suman[3]

[1]ICAR-Indian Veterinary Research Institute, Regional Station, Palampur-176061, H.P., India
[2]Division of Livestock Products Technology, ICAR-Indian Veterinary Research Institute, Bareilly-243122, U.P., India
[3]Department of Animal and Food Sciences, University of Kentucky, 405 W.P. Garrigus Building, Lexington, KY 40546, USA
*Corresponding author. Email: biswaslpt@gmail.com (Ashim Kumar Biswas)

Abstract: Meat's global appeal, driven by its nutritional richness and sensory attributes, encompasses high-quality proteins, bioavailable iron, and various bioactive compounds, especially B12 and iron. Palatability, assessed via juiciness, tenderness, and flavor, enhances its desirability. Despite these merits, meat is susceptible to lipid and protein oxidation by generating secondary metabolites aldehydes and carbonyls. Endogenous carnosine and anserine act as scavengers of these metabolites, thus enhancing meat's palatability. Additionally, meat houses an array of other bioactive compounds, including L-carnitine, taurine, conjugated linoleic acid, glutathione, alpha-lipoic acid, and bioactive peptides, each contributing to nutritional value of meat and exerting diverse physiological roles. This comprehensive review explores the various aspects of these bioactive compounds. Special emphasis is placed on carnosine and anserine, which exemplify the synergy of nutrition and palatability in the meat matrix. Insights into their pivotal roles in augmenting palatability and mitigating lipid oxidation offer a deeper understanding of the multifaceted benefits of bioactive compounds in meat.

Key words: bioactive compounds, meat palatability, nutrition, lipid oxidation
Meat and Muscle Biology 8(1): 16992, 1–15 (2024) **doi:10.22175/mmb.16992**
Submitted 30 September 2023 Accepted 7 December 2023

Introduction

Meat is a staple in diets worldwide, cherished not only for its essential proteins, vitamins, and minerals but also for its lipids, which are crucial both for human nutrition and meat quality by providing essential nutrients and amplifying flavor (Domínguez et al., 2019). Thus, nutrition and palatability are pivotal elements that are endorsed and relished by meat consumers (Kim and Jang, 2021). In the context of nutrition, the meat matrix encompasses high-quality proteins, bioavailable heme iron, and a multitude of advantageous bioactive compounds, rendering it a nutritionally efficacious option for consumers. Its richness in vital vitamins, especially B12 and iron, highlights its essential role in global nutrition (Leroy et al., 2023). Further, meat palatability is integral to consumer choice, primarily assessed by juiciness, tenderness and flavor. These elements are interlinked and contribute to the overall impression of meat's desirability, with juiciness relating to moisture sensation, tenderness to ease of chewing, and flavor to a combination of olfactory, gustatory, and textural sensations (Miller, 2014). Consumer perceptions of these attributes can differ, influenced by the inherent chemical and physical properties of the meat balance altered by various antemortem and postmortem factors. The intricate balance of muscle fibers, different types of fats, and connective tissue fundamentally impacts meat's overall palatability and has already been reviewed well and published in the *Encyclopedia of Meat Science* by Miller (2014).

However, both the nutrition and palatability of meat can be lessened by lipid and protein oxidation (Sottero et al., 2019). The oxidation mechanism is intricate, commencing with reactions involving

unsaturated fatty acids and proteins (Kunyaboon et al., 2021). Although post-slaughter endogenous factors of the muscle matrix like heme protein concentrations and inherent enzymes in muscles and saturation index in phospholipid membrane make it susceptible to lipid oxidation (Wu et al., 2022a, 2022b), the endogenous bioactive compounds like carnosine and anserine offer antioxidant properties to meat besides health benefits beyond their basic nutritional value (Klurfeld, 2018; Leroy et al., 2023). Carnosine and anserine, found in skeletal muscle, act as scavengers of aldehydes produced by the oxidative degradation of various biomolecules and play an important role in enhancing palatability (Zhang et al., 2020; Kim and Jang, 2021; Kajiya et al., 2023). Other bioactive compounds such as L-carnitine, taurine, conjugated linoleic acid, glutathione, alpha-lipoic acid, and bioactive peptides also present in meat, hold significant nutritional value, having multifarious physiological roles. For instance, L-carnitine is essential for energy metabolism and transporting fatty acids to the mitochondria, beneficial for Alzheimer's patients' learning capacity and memory (Kathuria et al., 2019). This review article will delve deeply into carnosine and anserine, along with others (L-carnitine, taurine, conjugated linoleic acid, glutathione, alpha-lipoic acid, and bioactive peptides) covering aspects such as their sources, concentrations in meat and derivatives, as well as their metabolism and functionalities. Moreover, insights will be provided into the pivotal roles of carnosine and anserine in augmenting palatability and mitigating lipid oxidation.

Bioactive Compounds

While meat is typically recognized for its protein, vitamin, and mineral content, it also serves as a source of essential bioactive compounds that, besides ensuring meat palatability, are crucial for the human body's optimal functioning (Prasow et al., 2019). These have been detailed in subsequent sections.

Carnosine

Carnosine (β-alanyl-L-histidine) is a natural, water-soluble, imidazole dipeptide derived from the amino acids B-alanine and L-histidine. Imidazole dipeptide is a term used for compounds made up of 2 smaller molecules (dipeptides) that are connected through histidine and contain an imidazole group; this compound is notably present in mammals, birds, and fish meat, particularly in muscle and brain tissues and in kidneys too. Carnosine was initially detected in beef extract during the early 1900s by W. Gulewitsch and S. Amiradzibi (Schmid, 2010).

Sources and concentration in humans. Consumption of food items such as seafood (prawns, tuna, mackerel), poultry, and red meats serve as dietary sources of β-alanine, contributing approximately 300–550 mg of β-alanine per day (Matthews et al., 2023). Variations in its endogenous concentrations can be attributed to distinctions in biological sex (predominantly elevated in males), senescence (declining as one ages), and dietary preferences (notably diminished in those adhering to plant-based diets). In human muscle tissues, carnosine concentrations average 20 mM/kg dry weight (Schmid, 2010), exhibiting a range of 5–10 mM on a wet weight basis and 15–40 mM/kg on a dry weight basis; substantial concentrations are also discerned in neural tissues and cerebral regions (Culbertson et al., 2010).

Biosynthesis and metabolism. Carnosine biosynthesis is facilitated through the enzymatic action of carnosine synthetase in conjunction with adenosine triphosphate (ATP) molecules. The endogenous production of carnosine within myofibrils is potentially contingent upon the systemic availability of β-alanine (Kulczyński et al., 2019). Earlier available literature emphasized a positive correlation between elevated histidine consumption and augmented carnosine tissue concentrations (Zięba, 2007). Additionally, certain external stress inducers, encompassing physical trauma, physiological shock, and nutritional deprivation, have demonstrated a propensity to attenuate carnosine concentrations within the myofibrillar structure of animals (Budzeń and Rymaszewska, 2013).

After digestion in the gastrointestinal tract, carnosine is effectively released from food, ensuring its maximum availability for absorption. This uptake of carnosine in the small intestine primarily occurs through the PepT1 peptide transporters, which are associated with protons (Marcolini et al., 2015). It breaks down in the body's serum and tissues, a process driven solely by the enzyme carnosinase (Figure 1).

Regular enzymes don't affect carnosine's breakdown, and it does not degrade on its own (Bellia et al., 2014). This shows that its metabolism is tightly controlled. Two forms of the carnosinase enzyme exist in humans: CN1 in the serum and brain and CN2 in tissues (Creighton et al., 2022). CN1 is notably active and breaks down both carnosine and a related molecule, homocarnosine, rapidly post-meal, explaining why carnosine is not usually found after fasting. This rapid

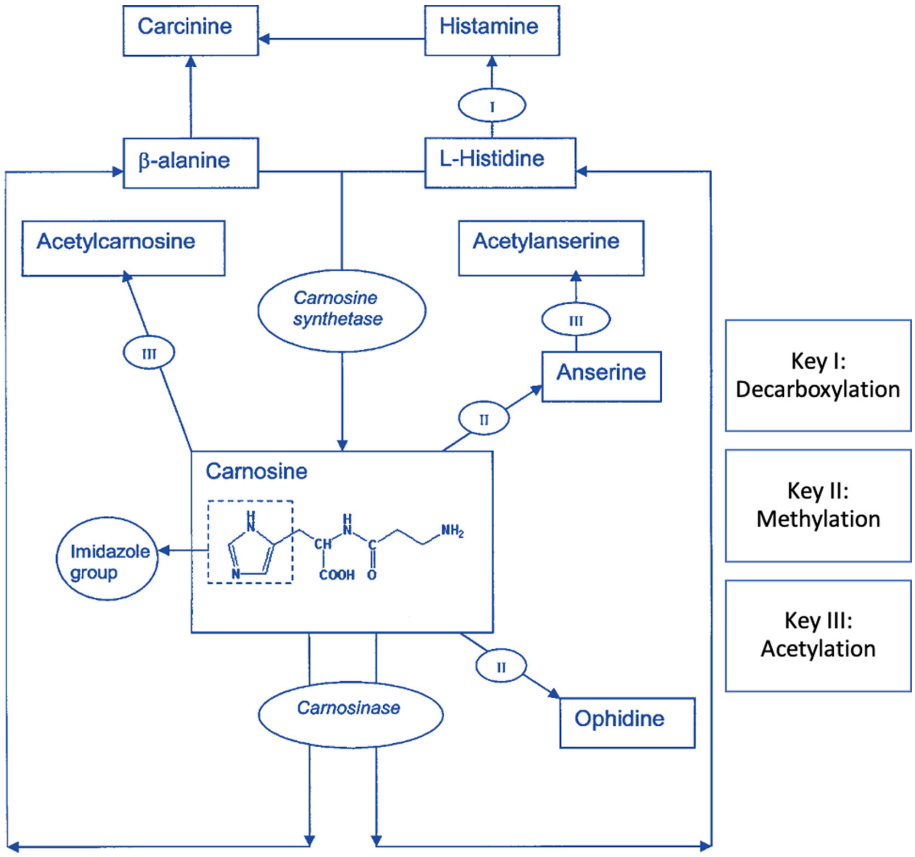

Figure 1. Pathway of carnosine metabolism [*Source:* (Begum et al., 2005)].

breakdown makes it challenging for therapeutic uses of carnosine. Additionally, recent research indicates that the human kidneys have their own carnosine processing system, with specific enzymes located in certain parts of the kidney. This may play a significant role in managing carnosine levels, especially concerning conditions like diabetic kidney disease (Baye et al., 2016; Jukić et al., 2021). In context to its metabolism, a study conducted by Gardner et al. (1991) reported that 14% of carnosine gets excreted as such in urine upon administration of a 4 g dose of carnosine, and this percentage was significantly dependent on the activity level of the enzyme carnosinase of plasma. A subsequent study investigated carnosine concentrations in blood plasma after the intake of a meal consisting of 200 g of minced beef (containing 124 mg of carnosine per 100 g of meat). The concentration of carnosine in the plasma ascended to its peak level of 32.7 mg/L 2.5 h post-consumption before experiencing a decline. Post 5.5 h, the presence of carnosine in the plasma was undetectable (Park et al., 2005).

Carnosine levels in meat and meat products. The carnosine levels in meat depend upon the type of muscle fiber, breed, and form (raw or cooked). For instance, raw Korean native chicken meat's carnosine concentration varied in red and white fibers and ranged from 160 to 201 mg/100 g for breast meat and 55 to 88 mg/100 g for leg meat (Jayasena et al., 2014). However, Thai indigenous and hybrid native chickens showcased greater carnosine concentrations viz. 621 to 818 mg/100 g in breast muscle and 271 to 363 mg/100 g in thigh muscle (Intarapichet and Maikhunthod, 2005). Predominantly, breast meat is packed with over 90% white fibers (type IIB), which rely mostly on anaerobic metabolism. This leads to lactic acid buildup, necessitating a higher carnosine content for its buffering capabilities (Dunnett and Harris, 2010). Further, cooking decreases its concentration due to its water-soluble nature, as observed by Jayasena et al. (2014). The raw meat boasted a carnosine content of 127.24 mg/100 g, which dropped to 99.43 mg/100 g once cooked. However, the reports suggested higher losses in white muscle fibers (78% retention) than in red muscle fibers (85% retention) (Jayasena et al., 2014). Different researchers have reported different carnosine levels in different meat species, and some have been detailed in Table 1. Furthermore, Aristoy and Toldrá (2004) quantified carnosine contents in various animal products as 313 mg/100 g in pork loin, 449 mg in pork ham,

Table 1. Carnosine levels in different species

Species	Source	Level (mg/100 g)	References
Cattle	*Semitendinosus*	453.0	(Purchas and Zou, 2008)
	Heart	32.6	
	Liver	77.5	
	Longissimus muscle	372.0	(Mateescu et al., 2012)
	Hanwoo beef	289.95	(Kwon and Choi, 2018)
	American beef	112.42	
	Australian beef	205.87	
	Muscle tissue of Limousin breed	462.48	(Solarczyk et al., 2020)
	Muscle tissue of Polish Holstein-Friesian (PHF)	387.3	
	Muscle tissue of PHF × Limousin	492.36	
Pork	Duroc *Longissimus thoracis*	246.84–353.47	(D'Astous-Pagé et al., 2017)
	Landrace *Longissimus thoracis*	242.91–322.47	
	Yorkshire *Longissimus thoracis*	254.05–333.64	
	Shoulder meat	270.0	Arihara and Ohata (2008)
	Loin	462.0	Mora et al. (2007)
Lamb	Polish Merino *Longissimus lumborum* (LL)	225.75	(Radzik-Rant et al., 2020)
	Polish Merino *Gluteus medius*	204.33	
	Polish Merino × Berrichone du Cher LL	226.54	
	Polish Merino × Berrichone du Cher *Gluteus medius*	208.22	
	Ram	333.5	(Purchas et al., 2004)
	Ewe	399	
	LL	491.1	
	Semitendinosus	356.7	
	Triceps brachii	251.1	
Chicken	Skeletal muscle (μg/g)	6.97	(Wang et al., 2021)
	HH (Commercial Native)	511.04	(Ali et al., 2019)
	Broiler	257.94	
	2A (New Native Strain)	287.39	
	2D (New Native Strain)	359.31	
Fish	Skeletal muscle of Katsuwonus (μg/g)	1.117	(Wang et al., 2021)

375 mg in beef loin, 39.3 mg in lamb shoulder, 180 mg in chicken breast, 63 mg in chicken thigh, and 66 mg per 100 g in turkey wings. In seafood, salmon contained 0.53 mg, trout 1.6 mg, and sardines only 0.1 mg per 100 g (Aristoy and Toldrá, 2004).

Functions. Carnosine, a multifaceted dipeptide, exhibits several critical biochemical roles, including pH buffering, scavenging of reactive oxygen species (ROS), modulation of enzymatic activity, and regulation of calcium flux within the sarcoplasmic reticulum (Begum et al., 2005). It serves as a potent proton buffer with an exceptional buffering capacity in muscle tissue. Consequently, it contributes to the stabilization of intramuscular pH, enhancing the anaerobic performance and increasing tolerance to hypoxic conditions (Culbertson et al., 2010). Carnosine plays a pivotal role in anti-aging mechanisms by aiding the advanced glycation end-products (AGE) scavenging macrophages to recognize and eliminate AGE molecules more efficiently (Chen et al., 2022). Additionally, carnosine interacts with methylglyoxal and potentially other harmful carbonyl species. Notably, methylglyoxal has been implicated in the synthesis of AGE and is associated with pathologies in age-linked diseases such as diabetes, arteriosclerosis, and Alzheimer's (Vongsawasdi and Noomhorm, 2014). From a pharmacological perspective, polaprezinc, a Zn(II) complex derivative of carnosine, exhibits efficacy against *Helicobacter pylori*, a primary etiological factor in gastric ulceration (Mahmoud et al., 2022).

Anserine

Following the unveiling of carnosine in beef, scientists extended their studies to different animal species. In 1929, N. Tolkatschevskaya and D. Ackermann discovered a compound in the skeletal muscle of geese resembling carnosine that was named "anserine" due to the goose's taxonomic name. Anserine (methyl

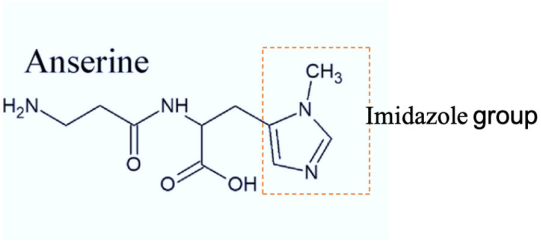

Figure 2. Structure of anserine [*Source*: Kumrungsee et al. (2022)].

carnosine) is a naturally occurring imidazole-dipeptide (β-alanyl-N-methyl-L-histidine) (Figure 2) (Wu, 2020).

Sources and concentration in humans. Anserine is found in the skeletal muscles of birds, particularly in chickens, and to some extent in certain species of fish (salmon, tuna, and trout) and beef. However, it is not present in human tissues, including the skeletal muscle, heart, and brain. Furthermore, in healthy adult humans who do not consume anserine, it is typically not detected in the plasma. Conversely, in non-primate animals, plasma levels of anserine range between 2 and 10 μM, varying based on the species (Everaert et al., 2019; Wu, 2020).

Biosynthesis and metabolism. Anserine's biosynthesis is ATP dependent, involving specific enzymes, primarily carnosine N-methyltransferase and to a lesser extent anserine synthetase due to 1-methylhistidine's limited availability (Wu, 2018). There exists a notable metabolic link between anserine and creatine syntheses, as carnosine 1-methyltransferase and guanidinoacetate methyltransferase compete for S-adenosylmethionine (Wu, 2013). Anserine's homeostasis in skeletal muscle is similarly regulated to carnosine's, being influenced by the availability or breakdown of β-alanine (Blancquaert et al., 2017; Wu, 2020).

Upon consumption by human beings, it gets digested slowly by carnosinase. The metabolism is similar to carnosine as detailed in the section "Biosynthesis and metabolism," but carnosinase acts more slowly on anserine than carnosine. Upon digestion, it gets absorbed in the small intestine and transported via the bloodstream. Excess anserine, along with β-alanine and 1-methyl-histidine, is eliminated in urine (Wu, 2020). Studies have shown that after ingesting specific amounts of anserine, its presence in urine rises, peaking about 90 min post-consumption (Everaert et al., 2019). Even with higher intake, the peak plasma concentration remains low, showing the peptide's extensive breakdown. Consuming beef or chicken broth markedly increases urinary anserine levels compared to not eating these meats (Yeum et al., 2010).

Levels in meat and meat products. Anserine is usually found in abundance in breast meat in comparison to thigh meat due to its role in buffering proton production in breast muscle (Jung et al., 2013). The anserine levels varied among beef cuts; for instance, in chuck, round, and loin, the content was found to be 2.79, 3.25, and 3.66 mg/g dry weight, respectively (Wu, 2020). Thornton et al. (2015) reported 8.5 mg and Mateescu et al. (2012) reported 67 mg anserine in 100 g of wet beef meat. Like carnosine, the levels of anserine in meat depend upon meat type and chicken line as given in Table 2. Although female thigh meat tends to have higher anserine levels than male thigh meat and male breast meat tends to have higher anserine content than female breast meat, exceptions are there in certain genetic lines (Jung et al., 2013). Further, Ali et al. (2019) also reported that the anserine concentration in male breast meat in commercial native chicken was 1526 mg/100 g and in strains 2A, 2C, and 2D was 1,286.34, 962.70, and 1,059.76 mg/100 g. Further, in broiler meat, it was reported to be 660.38 mg/100 g.

Functions. Anserine, like carnosine, plays several physiological roles. These include antioxidative functions, modulation of muscle contractility, and regulation of metabolism (Everaert et al., 2019). Additionally, anserine serves as a pH buffer in muscles, thus helping maintain the muscle's pH during periods of high activity (Jung et al., 2013). Since it is a methylated product of carnosine, anserine also possesses unique characteristics. For instance, unlike carnosine, it does not chelate copper and might have varying effects on cellular nitric oxide availability (Boldyrev et al., 2013). In terms of health implications, anserine's potential therapeutic effects have been observed in animal models for conditions like hyperglycemia and Alzheimer's disease (Kubomura et al., 2010; Kaneko et al., 2017; Peters et al., 2018). Preliminary human

Table 2. Variation in anserine content (mg/100 g) in different lines of Korean native chicken breeds and different types of muscle, adopted from Jung et al. (2013)

	Breast		Thigh	
Line	Male	Female	Male	Female
Black	880^{ab}	834	$321^{b,y}$	373^{x}
Gray-brown	851^{ab}	818	$330^{ab,y}$	367^{x}
Red-brown	803^{b}	803	$312^{b,y}$	343^{x}
White	$921^{a,x}$	824^{y}	361^{a}	374
Yellow-brown	$914^{a,x}$	848^{y}	$327^{ab,y}$	357^{x}

[a,b]Different letters among breeds differ significantly ($P < 0.05$).

[x,y]Different letters between sex differ significantly ($P < 0.05$)

studies have also pointed toward its positive influence on metabolic, neurological, cardiovascular, and renal functions (Kubomura et al., 2010; Kaneko et al., 2017; Peters et al., 2018).

L-carnitine

L-carnitine, scientifically known as γ-trimethylamino-β-hydroxy butyric acid or 3-hydroxy-4-N,N,N-trimethylaminobutyrate (Figure 3), was first identified in meat extracts in 1905 (Schmid, 2010; Kulczyński et al., 2019).

Sources and concentrations in humans. The main sources of L-carnitine in the diet are animal products, notably red meats such as beef and lamb. In contrast, plant-based foods offer minimal amounts, leading to reduced intake in vegetarians and vegans. Humans typically acquire about 75% of their L-carnitine from diet, with the body producing the other 25%. Intake averages 20–200 mg, higher in non-vegetarians due to meat consumption (Schmid, 2010; Kulczyński et al., 2019). The human body contains roughly 0.3 g/kg of L-carnitine, with 98% inside cells, mainly in muscles and liver. Extracellular fluid, liver, skeletal muscle, and kidneys have L-carnitine concentrations of 500, 1,300, 127,000, and 200 μM, respectively. While the liver has 0.5–1 μM/g, the skeletal muscle has a higher concentration at 3–5 μM/g (Adeva-Andany et al., 2017).

Biosynthesis and metabolism. L-carnitine is a quintessential molecule synthesized primarily in the liver, kidneys, and brain of mammals and is stored in various tissues, including the skeletal muscle, heart, brain, and nearly all other tissues (Bjørndal et al., 2013; Kulczyński et al., 2019). The primary amino acids essential for this synthesis are L-lysine, which offers the carbon skeleton, and L-methionine, responsible for supplying the N-methyl group. Notably, L-lysine undergoes methylation, catalyzed by a methyltransferase using S-adenosyl-L-methionine as the methyl donor, forming protein-linked 6-N-trimethyllysine. This compound, mostly present in skeletal muscle (accounting for about 65% of its total amount), is released following protein breakdown, a critical step in the L-carnitine synthesis pathway. Hydroxylation of trimethyllysine results in the formation of 3-hydroxy-6-N-trimethyllysine, facilitated by the enzyme 6-N-trimethyllysine hydroxylase, predominantly in the mitochondria. Subsequent enzymatic actions lead to the conversion of 3-hydroxy-6-N-trimethyllysine to c-butyrobetaine, mainly in the liver and kidneys. This pathway is further supported by key cofactors such as vitamin C, vitamin B6, niacin, and reduced iron (Bjørndal et al., 2013; Vongsawasdi and Noomhorm, 2014; Kulczyński et al., 2019).

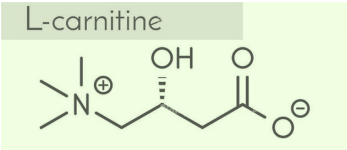

Figure 3. Structure of L-carnitine [*Source:* (Schmid, 2010)].

Concerning metabolism, the body maintains L-carnitine's balance through a combination of dietary intake, internal synthesis, and kidney reabsorption. The distribution of L-carnitine across cellular membranes is facilitated by specific transporters, notably the OCTN2 transporter. This transporter is pivotal in ensuring the muscle tissue, containing 90–95% of the body's total L-carnitine, has adequate levels. Any disruption or malfunction in the OCTN2 transporter can result in significant carnitine imbalances, impacting its essential metabolic functions (Bjørndal et al., 2013; Kulczyński et al., 2019). Approximately 65–75% of L-carnitine from food is absorbed in the small intestine, while the remainder is primarily broken down by microbes in the large intestine. A minor fraction is expelled in the feces. The L-carnitine concentration in the blood is controlled through the kidneys and varies based on age and gender. L-carnitine is excreted through the kidneys and bile (Schmid, 2010). Upon consumption, its effectiveness is influenced by bioavailability: 15–18% from supplements, but vegetarians have a bioavailability of 66–86%, compared to 54–72% in non-vegetarians (Czeczot and Ścibior, 2005).

Levels in meat. Differing levels of L-carnitine have been observed in varieties of meat and meat products. For instance, 100 g of beef steak contained 65.0 mg, minced beef 87.5 mg, skinless chicken breast 10.4 mg, turkey meat 21.2 mg, lamb chop 40.5 mg, pork shoulder 21.1 mg, ham 33.5 mg, veal 78.2 mg, merguez (beef sausage with lamb) 66.3 mg, pork sausage 7.1 mg, tuna fish 1.5 mg, and smoked salmon 1.0 mg (Schmid, 2010). Radzik-Rant et al. (2020) reported varied L-carnitine content *Longissimus lumborum* and *Gluteus medius* muscle of 2 different breeds of lamb as in Polish Merino 164.90 and 167.89 mg/100 g and in Polish Merino × Berrichone du Cher 165.42 and 170.76 mg/100 g, respectively.

Functions. L-carnitine is vital for human physiology, primarily aiding in energy production by transporting

long-chain fatty acids for β-oxidation. It supports muscle function, prevents skeletal muscle issues in heart failure, and contributes to amino acid metabolism. Notably, it also enhances antioxidant enzyme activity, potentially reducing oxidative stress and benefiting coronary heart disease patients. Supplementation of L-carnitine has therapeutic benefits, addressing various health conditions like heart diseases, type 2 diabetes, Alzheimer's, HIV, and male infertility. When given as acetyl-L-carnitine, it may enhance cognitive function in Alzheimer's patients (Czeczot and Ścibior, 2005; Schmid, 2010; Bjørndal et al., 2013). It is also indicated to reduce inflammation and deter fatty liver issues. However, L-carnitine's effect on fat metabolism and athletic performance is most pronounced in deficiency cases. It also impacts cholesterol levels, especially among type II diabetes patients. Insufficient L-carnitine can disrupt fatty acid processes, leading to significant health issues, such as heart and liver failure. Thus, ensuring adequate intake is crucial to prevent related health risks (Adeva-Andany et al., 2017; Kulczyński et al., 2019).

Taurine

Taurine, or 2-aminoethanesulfonic acid, is a distinctive sulfur-containing β-amino acid (Figure 4) prevalent in various mammalian tissues, notably the brain, retina, and muscles. It was first identified from bull's bile by scientists F. Tiedemann and L. Gmelin in 1827, and its name is derived from the Latin "*Bos taurus*," referring to a bull (Kulczyński et al., 2019; Wu, 2020).

Sources and concentration in humans. Taurine, abundant in mammalian and avian tissues like the blood, intestine, liver, muscle, heart, brain, kidneys, and retina, plays a crucial role as a nutrient, particularly emphasized by its presence in various mammals' milk. A 70-kg individual typically holds about 70 g of taurine, predominantly stored in skeletal muscles, accounting for nearly 70% of the total storage in adults. It is found in concentrations ranging between 15 and 40 mM in specific human tissues, including the heart, retina, and placenta. While it is prevalent in animal-based foods, it is scarcely found in plant-based products, which often leads to decreased serum taurine levels in vegetarians (Kulczyński et al., 2019).

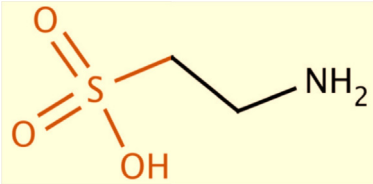

Figure 4. Structure of taurine [*Source:* (Schmid, 2010)].

Biosynthesis and metabolism. Taurine is primarily synthesized in the liver, with methionine, cysteine, and vitamin B6 playing pivotal roles. In humans, taurine is synthesized from cysteine, which is derived from methionine catabolism. While rats have a high capacity for taurine production, humans have reduced hepatic enzyme, cysteinesulfinate decarboxylase activity, limiting their synthesis (Schmid, 2010). A typical adult produces 50–125 mg daily, affected by dietary protein, nutrition, and enzyme activity. External factors can also impede production. Notably, infants and those on plant-based diets, which lack adequate taurine precursors, often face challenges in meeting their taurine needs (Kulczyński et al., 2019; Wu, 2020).

Dietary taurine is absorbed in the small intestine by enterocytes using the TauT transporter. After absorption, taurine remains unchanged in the intestinal mucosa and then enters the portal circulation. Increased dietary taurine intake leads to elevated taurine levels in key tissues such as the skeletal muscle, brain, and heart. Taurine metabolism in humans is selective, primarily involving specific pathways like transamination, oxidation, and oxygenation, which vary by species and cell type (Schmid, 2010; Vongsawasdi and Noomhorm, 2014). Taurine is crucial for bile salt formation, conjugating with bile acids in the liver. These salts, stored in the gallbladder, aid lipid digestion and, after use, move to the distal ileum where microbes partially hydrolyze them back into bile acids and taurine. Through enterohepatic circulation, the liver reabsorbs most of these components, ensuring sustained taurine levels and preventing long-term deficiency (Kulczyński et al., 2019; Wu, 2020).

Levels in meat. Taurine is notably abundant in animal-origin foods, especially beef and pork and seafood such as mussels and oysters. Beef and pork, for example, contain taurine concentrations between 43.1 and 61.2 mg/100 g (Vongsawasdi and Noomhorm, 2014). Some offals, like the pig heart, can have up to 200 mg of taurine per 100 g. The concentration of taurine varied considerably across different meats as observed by Laidlaw et al. (1990). In chickens, a contrast was observed between light and dark meat, with concentrations of 18 mg/100 g and 169 mg/100 g, respectively. Similarly, turkey's light meat had 30 mg/100 g, while its dark meat showed a significantly higher concentration at 306 mg/100 g. Beef and veal had relatively close concentrations, with 43 mg/100 g and 40 mg/100 g,

respectively. Pork loin and salami exhibited concentrations of 61 mg/100 g and 59 mg/100 g, respectively, whereas ham had 50 mg/100 g. Tuna fish in oil contained a concentration of 42 mg/100 g. However, marine organisms like oysters and mussels had markedly higher taurine levels, with concentrations of 396 mg/100 g and 655 mg/100 g, respectively.

Functions. Taurine, distinct from other amino acids due to its inability to form peptide bonds, does not participate in protein synthesis. Its functionality spans a range of physiological activities, such as osmoregulation, immunomodulation, and bile salt formation. Serving as an effective antioxidant, taurine mitigates the reactivity of potent oxidants by forming stable compounds with them. It is integral to lipid and carbohydrate metabolism and can modulate insulin secretion and sensitivity (Schmid, 2010; Vongsawasdi and Noomhorm, 2014). The implications of taurine are broad, impacting cardiovascular health and providing protective effects to the retina, likely mitigating oxidative stress and promoting retinal cell differentiation. Its substantial concentrations in the cerebral cortex and hippocampus suggest its role as a neurotransmitter and neuromodulator. The benefits of taurine are observed across diverse body systems, including but not limited to cardiovascular, digestive, endocrine, immune, muscular, neurological, reproductive, and visual systems (Kathuria et al., 2019; Kumrungsee et al., 2022).

Conjugated linoleic acid

Conjugated linoleic acid (CLA) refers to a group of geometric and positional isomers (Figure 5) of linoleic acid (cis-9, cis-12 18:2) characterized by unique configurations of double bonds in their carbon chain (Kulczyński et al., 2019).

Sources and concentrations in humans. The primary dietary sources of CLA are ruminant meats and dairy products. Ruminant animals, such as cattle, sheep, and goats, synthesize CLA in their rumen through the microbial transformation of unsaturated fatty acids like linoleic acid. CLA concentrations in meat vary depending on factors like animal diet and breed. Human daily intake of CLA can range from 50 to 500 mg/day, influenced by dietary habits and CLA content in animal products (Zhao et al., 2009; Koba and Yanagita, 2014).

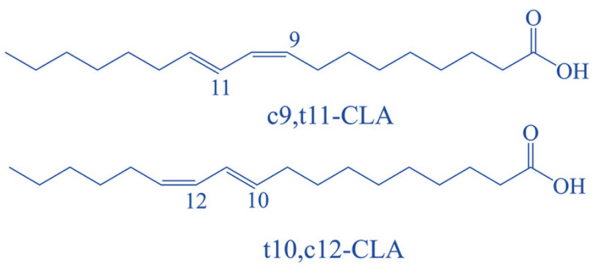

Figure 5. Structure of conjugated linoleic acid [*Source:* (Schmid, 2010)].

Biosynthesis and metabolism. CLA synthesis primarily occurs in the rumen of ruminant animals, where bacteria like *Butyrivibrio fibrisolvens* play a crucial role in converting unsaturated fatty acids into CLA isomers. These isomers exit the rumen, get absorbed through the small intestine, and are incorporated into tissues. In addition to rumen synthesis, the mammary glands of dairy cows can further convert trans-fatty acids into CLA isomers. The synthesis of CLA can also be achieved on a commercial scale through alkaline isomerization of oils rich in linoleic acid (Bauman et al., 2000; Koba and Yanagita, 2014).

Levels in meat. The concentration of CLA in meat is dependent on various factors, including the type of animal, cut of meat, and the animal's diet. For instance, lamb typically contains higher CLA levels (4.3 to 19.0 mg/g fat) compared to beef (1.2 to 10.0 mg/g fat). Pork, horsemeat, and chicken have much lower CLA concentrations, often below 1 mg/g fat (Koba and Yanagita, 2014; Vongsawasdi and Noomhorm, 2014).

Functions. CLA exhibits various biological activities and potential health benefits. Studies have indicated its role in body mass reduction, enhanced lipolysis in adipocytes, increased beta-oxidation of fatty acids, and potential impacts on lipid profiles. CLA may also influence carbohydrate metabolism, possess hypotensive properties and anti-inflammatory and immunomodulatory activity, and affect serum lipid profiles. However, research results are inconsistent, with some studies not confirming its biological activity and potential risks associated with certain CLA isomers (Zhao et al., 2009; Koba and Yanagita, 2014).

Glutathione

Glutathione, also known as GSH, is a crucial tripeptide composed of 3 amino acids: glutamic acid, cysteine, and glycine (Figure 6). It is a low molecular weight, water-soluble compound that is found in various cells, both in plants and animals, including humans (Allen and Bradley, 2011).

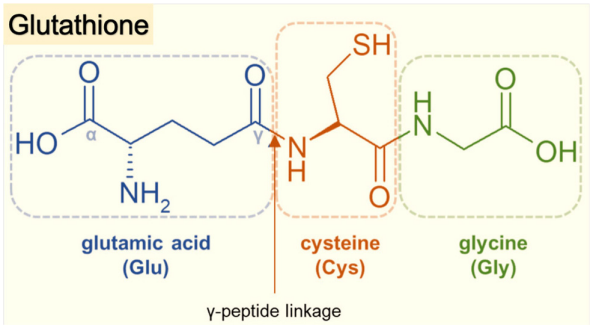

Figure 6. Structure of conjugated linoleic acid [*Source:* (Allen and Bradley, 2011)].

Sources and concentrations in human. The dietary sources of GSH vary, with vegetables, fruits, and cooked meat being some of the primary sources. Additionally, foods rich in methionine and cysteine, such as meat (including beef and poultry), eggs, and milk (from cows, ewes, and goats), contribute significantly to GSH levels in the body (Bukowska, 2004). The concentration of GSH in human cells is relatively stable, and its levels can be influenced by various factors. High protein intake has been associated with an increase in GSH concentration, while conditions like hyperthyroidism can reduce GSH levels by up to 40% (Allen and Bradley, 2011).

Biosynthesis and metabolism. GSH is primarily synthesized in hepatocytes and then transported through the bloodstream to different tissues. The synthesis of GSH in the body relies on several factors, including the availability of substrates like cysteine, the concentration of γ-glutamyl-cysteine synthetase required for synthesis, and the existing GSH concentration within the cell (Allen and Bradley, 2011). GSH administered orally has limited bioavailability and may not directly reach the cells; however, its amino acid constituents can serve as substrates for the cell's own GSH synthesis.

Levels in meat. Meat, especially when fresh and uncooked, is known to contain significant amounts of GSH due to its cysteine content. However, it is important to note that GSH levels in meat can be affected by various factors, including processing methods. For instance, canning, drying, and curing processes can lead to substantial losses of GSH in meat products (Allen and Bradley, 2011). Beef steak and pork chop are considered good sources of GSH, with varying levels of both reduced (GSH) and oxidized (GSSG) glutathione present in these meat products (Kulczyński et al., 2019). Specifically, beef steak may contain GSH levels of approximately 12.3 mg/100 g and GSSG levels of about 13.4 mg/100 g, whereas pork chop could have GSH levels of around 18.9 mg/100 g and GSSG levels of approximately 23.6 mg/100 g. High concentrations of GSH are typically reported in tissues such as the kidneys, brain, erythrocytes, leukocytes, lungs, heart, intestines, and muscles (Schmid, 2010; Allen and Bradley, 2011).

Functions. The primary function of GSH in living organisms is to serve as a potent intracellular antioxidant. GSH is involved in various cellular processes, including detoxification of oxidative stress products and protection against ROS, such as hydroxyl radicals, hydrogen peroxides, lipid peroxides, and superoxide anions (Bukowska, 2004). GSH efficiently scavenges ROS, protecting cells from oxidative damage to DNA and proteins (Bukowska, 2004). It also plays a vital role in detoxifying harmful chemicals, including heavy metals, and may protect against the detrimental effects of factors such as cigarette smoke and alcohol abuse. Furthermore, GSH is essential for various biological processes, including the regulation of gene expression, DNA and protein synthesis, immune system function, cell growth, and signal transmission (Kulczyński et al., 2019). Reduced GSH levels have been linked to several diseases, including diabetes, alcoholism, AIDS, and neurodegenerative disorders like Alzheimer's and Parkinson's disease. Conversely, higher GSH levels can enhance the body's immune function by supporting natural killer cell cytotoxicity and lymphocyte proliferation while limiting oxidation reactions (Richie et al., 2015).

Bioactive peptides

Bioactive peptides are typically short chains of amino acids, usually consisting of 2 to 20 amino acids, although there are exceptions where they can be longer. These peptides have positive physiological effects when consumed in appropriate amounts. They originate from a wide range of food sources, including both plant and animal origins (Kulczyński et al., 2019). Notably, animal-based products like milk, eggs, bovine blood, collagen, gelatin, and various fish species, such as salmon, tuna, and herring are significant sources of bioactive peptides (Madhu et al., 2022).

Sources and levels in meat. Bioactive peptides are present in chicken, beef, pork, duck, mutton, and other types of meat (Madhu et al., 2022). Meat, in particular, contains high-quality proteins with all essential amino acids and is easily digestible (Bechaux et al., 2019). In addition to muscle tissue, other components of animals, such as skin, bone, and blood, can also serve as

sources of bioactive peptides through protein hydrolysis. However, the structural integrity of proteins is susceptible to temperature and pH variations, which can occur during meat processing steps like curing, drying, salting, fermentation, storage, freezing, and cooking. Consequently, temperature and pH modifications play a pivotal role in facilitating the production of bioactive peptides by either disrupting the spatial protein structure or cleaving peptide chains (Xing et al., 2019). In meat, bioactive peptides can be derived from different types of meat, including chicken, beef, pork, duck, and mutton (Madhu et al., 2022). The production of these peptides is influenced by factors such as temperature, pH, and processing methods. Freezing meat, for example, can lead to the generation of peptides depending on temperature and storage time (Xing et al., 2019).

Biosynthesis and metabolism. Bioactive peptides can be synthesized from precursor proteins using methods such as proteolysis in the intestinal tract, chemical or enzymatic hydrolysis in vitro, during food processing, or through microbial fermentation (Vongsawasdi and Noomhorm, 2014). Enzymatic hydrolysis is a common method used to produce bioactive peptides from meat proteins, employing various digestive enzymes like pepsin, trypsin, pancreatin, alcalase, and others, depending on the desired outcome (Mora et al., 2014; Madhu et al., 2022). The bioactivity of these peptides hinges on factors such as amino acid composition, specific sequence, N- and C-terminal ends, hydrophobic and hydrophilic properties, as well as peptide mass and length (Mora et al., 2014).

Molecular genetic engineering methods have also been developed to facilitate peptide synthesis when the amino acid sequence is known. The structure, composition of amino acids, specific sequence, and peptide length all influence the activity of bioactive peptides (Mora et al., 2014). These peptides can be absorbed from the intestine and transported through the circulatory system to target sites for exerting their bioactivity. While many studies have demonstrated in vitro bioactivity, it is crucial to test their in vivo effects due to potential changes during digestion and absorption (Vongsawasdi and Noomhorm, 2014; Madhu et al., 2022).

Functions. Bioactive peptides exhibit various physiological functions, including angiotensin-converting-enzyme inhibition to reduce arterial blood pressure. Additionally, these peptides possess antioxidant properties, allowing them to scavenge radicals and reducing or chelating metal ions (Xing et al., 2019; Madhu et al., 2022). Some bioactive peptides also demonstrate antibacterial effects against pathogenic microorganisms, making them potential candidates for food preservation. The aging of meat such as in the production of dry-cured hams can positively impact the formation of bioactive peptides, further promoting their consumption (Mora et al., 2014).

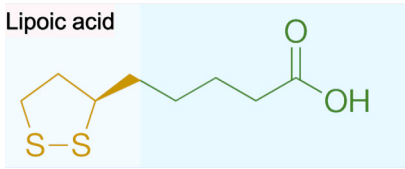

Figure 7. Structure of lipoic acid [*Source:* (Schmid, 2010)].

α-Lipoic acid

Lipoic acid, commonly identified as thioctic acid or α-lipoic acid, is an organosulfur compound that is an integral coenzyme in metabolic enzymatic processes, particularly within mitochondrial bioenergetic reactions (Tripathi et al., 2023). It is structurally characterized by its eight-carbon chain with 2 sulfur atoms at the 6th and 8th positions (Figure 7). Lipoic acid is present in both plant and animal sources, with vegetables like spinach, collard greens, broccoli, and tomatoes being rich sources. While it is less abundant in the animal kingdom, organs like the liver, kidneys, and heart have slightly higher levels compared to muscle tissues. Lipoic acid is synthesized in mitochondria from octanoic acid and cysteine and exists in 2 forms: the natural R-enantiomer and the S-enantiomer. Its crucial role lies in converting nutrient energy into ATP and participating in various mitochondrial multienzyme complexes, including pyruvate dehydrogenase, alpha-ketoglutarate dehydrogenase, and branched-chain keto-acid dehydrogenase (Schmid, 2010; Vongsawasdi and Noomhorm, 2014; Kulczyński et al., 2019; Tripathi et al., 2023). Additionally, it possesses significant antioxidant properties. Lipoic acid, along with its reduced form dihydrolipoic acid, reinforces the body's antioxidant defenses by neutralizing various ROS. Notably, it can function effectively in both aqueous and lipid environments, playing a role in regenerating other antioxidants like vitamins C and E (Schmid, 2010; Kathuria et al., 2019).

Bioactive Compounds and Meat Palatability

The concept of meat palatability is multifaceted, encompassing aspects such as juiciness, tenderness,

and flavor. The complexity arises due to the multitude of factors influencing each component, leading to potential interactions among these factors, thereby affecting various dimensions of palatability simultaneously (Miller, 2023). Among all, the flavor of meat plays a pivotal role in consumers' acceptance. Multiple intrinsic and extrinsic factors govern the overall eating quality of meat, with flavor standing out as the predominant determinant (Arshad et al., 2018). Meat flavor is closely linked with its taste profile, and the co-existence of carnosine and anserine plays a pivotal role in amplifying the same (Kajiya et al., 2023). Recent research related to meat taste exhibited the impact of the imidazole content ratio (carnosine to anserine ratio) on meat flavor. Kajiya et al. (2023) reported substantial correlations have been discerned between the aggregate content of imidazole dipeptides and the sensory assessments of meat. Specifically, R^2 values of 0.9872, 0.8224, and 0.9526 were documented for samples of beef, pork, and duck, respectively, evidencing a close relationship between the concentration of these dipeptides and the perceived organoleptic attributes. In the study, upon individual assessment, carnosine was found to impart a distinct bitter undertone to the meat. In contrast, the presence of anserine not only counteracted this bitterness but also elevated the umami or savory quality. The unique capability of anserine to veil bitterness suggests its potential as a taste modulator in meat. Furthermore, the enhanced umami sensation can be attributed to the synergistic interplay between anserine and carnosine. Zhang et al. (2020) documented a significant influence of carnosine and anserine, especially of anserine on the flavor profiles in chicken soups. With a taste activity value (TAV) of 6.19 in chicken breast meat soup, anserine's impact was particularly notable. Conversely, carnosine, with a TAV of 2.34 in the same soup, consistently modulates taste across different soup varieties.

Moreover, carnosine influences meat palatability through a combination of flavor altering properties, promoting the production of desirable roasty volatiles, preserving the inherent flavor by preventing oxidative rancidity and maintaining the visual appeal of the meat through color preservation (Aliani et al., 2013). The presence of carnosine in oxidized liposomes results in a shift in the distribution of volatiles, which may lead to changed flavor properties. In a model system with ribose and cysteine in equimolar concentrations, carnosine has been linked to the creation of roasty volatiles, which are compounds contributing to the desirable roasted or cooked flavor of the meat (Chen and Ho, 2002). Carnosine's antioxidative properties inhibit the formation of lipid peroxides and thiobarbituric acid-reactive substances. This leads to a decrease in sensory oxidative rancidity, thereby preserving the fresh and natural flavor of the meat (Aliani et al., 2013).

Furthermore, anserine has the dual function of mitigating bitterness and accentuating the savory umami profile (Kajiya et al., 2023). Through its antioxidant properties, anserine can suppress the production of reactive carbonyl species that contribute to off-flavors and bitter notes. Simultaneously, it possibly chelates certain metal ions, which intensify bitterness. Moreover, by interacting with taste receptors or modulating flavor compounds, anserine boosts the perception of the umami taste, further enriching the overall flavor of the meat (Domínguez et al., 2019; Kajiya et al., 2023). Thus, carnosine and anserine, integral components in the taste profile of meat, distinctly modulate the gustatory experience, with carnosine imparting sour notes and anserine enhancing umami flavors, respectively (Zhang et al., 2020).

Bioactive compounds and lipid oxidation

Lipid oxidation is a critical factor behind meat quality deterioration, beginning from the animal's sacrifice and continuing throughout processing and storage, leading to loss in nutritional value and undesired sensory changes (Min and Ahn, 2005; Domínguez et al., 2019) This complex process in meat is driven by elements like ROS and reactive nitrogen species (RNS) and metal ions. Unsaturated fatty acid and oxygen interact indirectly and activate the oxygen that produces radicals that promote oxidative reactions, influenced by factors such as light, temperature, and metal ions (Hadidi et al., 2022).

Auto-oxidation, driven by the interaction of unsaturated fatty acids with atmospheric oxygen, contributes to the oxidative deterioration of meat and runs in 3 phases: initiation, propagation, and termination phase. The whole process generates an array of compounds, notably aldehydes such as malondialdehyde (MDA), that have a profound impact on the flavor, aroma, and quality of meat products (Domínguez et al., 2019; Musakhanian et al., 2022; Geng et al., 2023). This MDA is a highly reactive aldehyde and does not limit its reactivity to lipids alone. It targets non-lipid substrates, particularly proteins, within the meat matrix. This electrophilic aldehyde attacks nucleophilic groups on proteins, resulting in the generation of carbonyl compounds (Wazir et al., 2021).

This concern is endogenously addressed by carnosine and anserine, and their antioxidative mechanisms

in meat preservation are multifaceted. Their ability to chelate metal ions, scavenge reactive species, neutralize aldehydes, and offer post-irradiation protection makes them invaluable natural preservatives for enhancing the quality and shelf life of meat products. Anserine and carnosine effectively mitigate fat oxidation and metmyoglobin formation. The latter is particularly crucial as metmyoglobin is responsible for the undesirable brown color in meat. These compounds aid in preserving the meat's inherent color and flavor, leading to an extended storage life (Schmid, 2010). The antioxidant mechanism has been briefed in the subsequent subsections. Further, between carnosine and anserine, carnosine is more capable of effectively inhibiting lipid oxidation in meat products and has been found to be more potent than other known antioxidants like α-tocopherol and BHT (Cuppett, 2001).

Chelation

Transition metal ions, well-documented accelerators of lipid oxidation, are effectively inhibited by carnosine, particularly iron and copper-catalyzed oxidation. Carnosine and anserine form complexes with these metals, which protects cells from potential metal-induced oxidative damage and thus can deter certain oxidative reactions that compromise meat quality (Cuppett, 2001; Kulczyński et al., 2019).

Scavenging

Carnosine and anserine are adept at ROS and RNS, defending cells against oxidative damage. The established scavenging capacity is vital not only for meat preservation but also for cellular defense, maintaining the structural and functional integrity of cells and tissues (Schmid, 2010; Jukić et al., 2021).

Neutralization

Oxidative processes in meat and other biological systems can lead to the formation of reactive aldehydes. Carnosine also neutralizes MDA, which can otherwise inflict damage to lipids and protein structure (Kulczyński et al., 2019; Jukić et al., 2021; Wazir et al., 2021). As per the literature, carnosine's antioxidative attributes are beneficial, especially in the post-irradiation phase of meat products like ground beef. It has been observed to reduce oxidative reactions and decrease metmyoglobin content, particularly during prolonged storage, thus further extending the shelf life of these products (Badr, 2007).

Summary and Conclusions

Bioactive compounds present in meat play a crucial role in enhancing both its nutritional value and sensory appeal. Carnosine and anserine have the ability to improve meat palatability by influencing its flavor profile, reducing bitterness, and enhancing umami notes. Moreover, these compounds serve as strong antioxidants, safeguarding meat from lipid oxidation and preserving its color, flavor, and overall quality. In conclusion, bioactive compounds, with a specific focus on carnosine and anserine, contribute significantly to the overall quality of meat. Their dual role in enhancing taste and protecting against oxidation underscores their importance in meat production and consumption. Understanding and harnessing the potential of these compounds can lead to improved meat products that offer not only superior sensory experiences but also prolonged shelf life and enhanced nutritional benefits for consumers.

Literature Cited

Adeva-Andany, M. M., I. Calvo-Castro, C. Fernández-Fernández, C. Donapetry-García, and A. M. Pedre-Piñeiro. 2017. Significance of L-carnitine for human health. IUBMB Life 69:578–594. https://doi.org/10.1002/iub.1646

Ali, M., S.-Y. Lee, J.-Y. Park, S. Jung, C. Jo, and K.-C. Nam. 2019. Comparison of functional compounds and micronutrients of chicken breast meat by breeds. Food Science of Animal Resources 39:632–642. https://doi.org/10.5851/kosfa.2019.e54

Aliani, M., D. Ryland, J. Williamson, and N. Rempel. 2013. The synergistic effect of ribose, carnosine, and ascorbic acid on the sensory and physico-chemical characteristics of minced bison meat. Food Science & Nutrition 1:172–183. https://doi.org/10.1002/fsn3.25

Allen, J., and R. D. Bradley. 2011. Effects of oral glutathione supplementation on systemic oxidative stress biomarkers in human volunteers. J. Altern. Complem. Med. 17:827–833.

Arihara, K., and M. Ohata. 2008. Bioactive compounds in meat. In: Meat biotechnology. Springer, New York. p. 231–249. https://doi.org/10.1007/978-0-387-79382-5_11

Aristoy, M. C., and F. Toldrá. 2004. Histidine dipeptides HPLC-based test for the detection of mammalian origin proteins in feeds for ruminants. Meat Sci. 67:211–217. https://doi.org/10.1016/j.meatsci.2003.10.008

Arshad, M. S., M. Sohaib, R. S. Ahmad, M. T. Nadeem, A. Imran, M. U. Arshad, J.-H. Kwon, and Z. Amjad. 2018. Ruminant meat flavor influenced by different factors with special reference to fatty acids. Lipids Health Dis. 17:223. https://doi.org/10.1186/s12944-018-0860-z

Badr, H. M. 2007. Antioxidative activity of carnosine in gamma irradiated ground beef and beef patties. Food Chem. 104:665–679. https://doi.org/10.1016/j.foodchem.2006.12.015

Bauman, D. E., L. H. Baumgard, B. A. Corl, and J. M. Griinari. 2000. Biosynthesis of conjugated linoleic acid in ruminants. J. Anim. Sci. 77:1–15. https://doi.org/10.2527/jas2000.77E-Suppl1f

Baye, E., B. Ukropcova, J. Ukropec, A. Hipkiss, G. Aldini, and B. de Courten. 2016. Physiological and therapeutic effects of carnosine on cardiometabolic risk and disease. Amino Acids 48:1131–1149. https://doi.org/10.1007/s00726-016-2208-1

Bechaux, J., P. Gatellier, J. F. Le Page, Y. Drillet, and V. Sante-Lhoutellier. 2019. A comprehensive review of bioactive peptides obtained from animal byproducts and their applications. Food Funct. 10:6244–6266. https://doi.org/10.1039/C9FO01546A

Begum, G., A. Cunliffe, and M. Leveritt. 2005. Physiological role of carnosine in contracting muscle. Int. J. Sport Nutr. Exe. 15:493–514. https://doi.org/10.1123/ijsnem.15.5.493

Bellia, F., G. Vecchio, and E. Rizzarelli. 2014. Carnosinases, their substrates and diseases. Molecules 19:2299–2329. https://doi.org/10.3390/molecules19022299

Bjørndal, B., T. Brattelid, E. Strand, N. F. Vigerust, G. F. T. Svingen, A. Svardal, O. Nygård, and R. K. Berge. 2013. Fish oil and the pan-PPAR agonist tetradecylthioacetic acid affect the amino acid and carnitine metabolism in rats. PLoS One 8:e66926. https://doi.org/10.1371/journal.pone.0066926

Blancquaert, L., I. Everaert, M. Missinne, A. Baguet, S. Stegen, A. Volkaert, M. Petrovic, C. Vervaet, E. Achten, M. De Maeyer, S. De Henauw, and W. Derave. 2017. Effects of histidine and β-alanine supplementation on human muscle carnosine storage. Med. Sci. Sport. Exer. 49:602–609. https://doi.org/10.1249/MSS.0000000000001213

Boldyrev, A. A., G. Aldini, and W. Derave. 2013. Physiology and pathophysiology of carnosine. Physiol. Rev. 93:1803–1845. https://doi.org/10.1152/physrev.00039.2012

Budzeń, S., and J. Rymaszewska. 2013. The biological role of carnosine and its possible applications in medicine. Adv. Clin. Exp. Med. 22:739–744.

Bukowska, B. 2004. Glutation: Biosynteza, czynniki indukujące oraz stężenie w wybranych jednostkach chorobowych [Glutathione: its biosynthesis, inducation agents and concentrations in selected units]. Med. Pr. 55:501–509.

Chen, Y., and C.-T. Ho. 2002. Effects of carnosine on volatile generation from maillard reaction of ribose and cysteine. J. Agr. Food Chem. 50:2372–2376. https://doi.org/10.1021/jf011244l

Chen, C., J. Zhang, L. Li, M. Guo, Y. He, Y. Dong, H. Meng and F. Yi. 2022. Advanced glycation end products in the skin: Molecular mechanisms, methods of measurement, and inhibitory pathways. Front. Med. 9. https://doi.org/10.3389/fmed.2022.837222

Creighton, J. V., L. de Souza Gonçalves, G. G. Artioli, D. Tan, K. J. Elliott-Sale, M. D. Turner, C. L. Doig, and C. Sale. 2022. Physiological roles of carnosine in myocardial function and health. Adv. Nutr. 13:1914–1929.

Culbertson, J. Y., R. B. Kreider, M. Greenwood, and M. Cooke. 2010. Effects of beta-alanine on muscle carnosine and exercise performance: A review of the current literature. Nutrients 2:75–98. https://doi.org/10.3390/nu2010075

Cuppett, S. L. 2001. The use of natural antioxidants in food products of animal origin. In: J. Pokorný, N. Yanishlieva, and M. Gordon, editors, Antioxidants in food: Practical applications. CRC Press, Boca Raton, FL. p. 285–310. https://doi.org/10.1016/9781855736160.4.285

Czeczot, A., and D. Ścibior. 2005. Role of L-carnitine in metabolism, nutrition and therapy. Postepy Hig. Med. Dosw. 59:9–19.

D'Astous-Pagé, J., C. Gariépy, R. Blouin, S. Cliche, B. Sullivan, F. Fortin, and M.-F. Palin. 2017. Carnosine content in the porcine *longissimus thoracis* muscle and its association with meat quality attributes and carnosine-related gene expression. Meat Sci. 124:84–94. https://doi.org/10.1016/j.meatsci.2016.11.004

Domínguez, R., M. Pateiro, M. Gagaoua, F. J. Barba, W. Zhang, and J. M. Lorenzo. 2019. A comprehensive review on lipid oxidation in meat and meat products. Antioxidants 8:429. https://doi.org/10.3390/antiox8100429

Dunnett, M., and R. C. Harris. 2010. Carnosine and taurine contents of type I, IIA and IIB fibres in the middle gluteal muscle. Equine Vet. J. 27:214–217. https://doi.org/10.1111/j.2042-3306.1995.tb04922.x

Everaert, I., G. Baron, S. Barbaresi, E. Gilardoni, C. Coppa, M. Carini, G. Vistoli, T. Bex, J. Stautemas, L. Blancquaert, W. Derave, G. Aldini, and L. Regazzoni. 2019. Development and validation of a sensitive LC–MS/MS assay for the quantification of anserine in human plasma and urine and its application to pharmacokinetic study. Amino Acids 51:103–114. https://doi.org/10.1007/s00726-018-2663-y

Gardner, M. L., K. M. Illingworth, J. Kelleher, and D. Wood. 1991. Intestinal absorption of the intact peptide carnosine in man, and comparison with intestinal permeability to lactulose. J. Physiol. 439:411–422. https://doi.org/10.1113/jphysiol.1991.sp018673

Geng, L., K. Liu, and H. Zhang. 2023. Lipid oxidation in foods and its implications on proteins. Frontiers in Nutrition 10. https://doi.org/10.3389/fnut.2023.1192199

Hadidi, M., J. C. Orellana-Palacios, F. Aghababaei, D. J. Gonzalez-Serrano, A. Moreno, and J. M. Lorenzo. 2022. Plant by-product antioxidants: Control of protein-lipid oxidation in meat and meat products. LWT-Food Sci. Technol. 169:114003. https://doi.org/10.1016/j.lwt.2022.114003

Intarapichet, K.-O., and B. Maikhunthod. 2005. Genotype and gender differences in carnosine extracts and antioxidant activities of chicken breast and thigh meats. Meat Sci. 71:634–642. https://doi.org/10.1016/j.meatsci.2005.05.011

Jayasena, D. D., S. Jung, Y. S. Bae, S. H. Kim, S. K. Lee, J. H. Lee, and C. Jo. 2014. Changes in endogenous bioactive compounds of Korean native chicken meat at different ages and during cooking. Poult Sci. 93:1842–1849. https://doi.org/10.3382/ps.2013-03721

Jukić, I., N. Kolobarić, A. Stupin, A. Matić, N. Kozina, Z. Mihaljević, M. Mihalj, P. Šušnjara, M. Stupin, Ž. B. Ćurić, K. Selthofer-Relatić, A. Kibel, A. Lukinac, L. Kolar, G. Kralik, Z. Kralik, A. Széchenyi, M. Jozanović, O. Galović, M. Medvidović-Kosanović, and I. Drenjančević. 2021. Carnosine, small but mighty—Prospect of use as functional ingredient for functional food formulation. Antioxidants 10:1037. https://doi.org/10.3390/antiox10071037

Jung, S., Y. S. Bae, H. J. Kim, D. D. Jayasena, J. H. Lee, H. B. Park, K. N. Heo, and C. Jo. 2013. Carnosine, anserine, creatine, and inosine 5′-monophosphate contents in breast and thigh meats from 5 lines of Korean native chicken. Poultry Sci. 92:3275–3282. https://doi.org/10.3382/ps.2013-03441

Kajiya, K., M. Arino, A. Koshio, and Y. Minami. 2023. Composition and taste of beef, pork, and duck meat and bioregulatory functions of imidazole dipeptides in meat. Sci. Rep.-UK 13:2125. https://doi.org/10.1038/s41598-023-29351-z

Kaneko, J., A. Enya, K. Enomoto, Q. Ding, and T. Hisatsune. 2017. Anserine (beta-alanyl-3-methyl-L-histidine) improves neurovascular-unit dysfunction and spatial memory in aged AβPPswe/PSEN1dE9 Alzheimer's-model mice. Sci. Rep.-UK 7:12571. https://doi.org/10.1038/s41598-017-12785-7

Kathuria, D., S. Gautam, S. Sharma, and K. D. Sharma. 2019. Animal based bioactives for health and wellness. Food & Nutrition Journal 4:203.

Kim, H.-J., and A. Jang. 2021. Correlations between the levels of the bioactive compounds and quality traits in beef loin and round during cold storage. Food Control 120:107491. https://doi.org/10.1016/j.foodcont.2020.107491

Klurfeld, D. M. 2018. What is the role of meat in a healthy diet? Animal Frontiers 8:5–10. https://doi.org/10.1093/af/vfy009

Koba, K., and T. Yanagita. 2014. Health benefits of conjugated linoleic acid (CLA). Obes. Res. Clin. Pract. 8:e525–e532. https://doi.org/10.1016/j.orcp.2013.10.001

Kubomura, D., Y. Matahira, K. Nagai, and A. Niijima. 2010. Effect of anserine ingestion on the hyperglycemia and autonomic nerves in rats and humans. Nutr. Neurosci. 13:123–128. https://doi.org/10.1179/147683010X12611460764048

Kulczyński, B., A. Sidor, and A. Gramza-Michałowska. 2019. Characteristics of selected antioxidative and bioactive compounds in meat and animal origin products. Antioxidants 8:335. https://doi.org/10.3390/antiox8090335

Kumrungsee, T., P. Zhang, N. Yanaka, T. Suda, and N. Kato. 2022. Emerging cardioprotective mechanisms of vitamin B6: A narrative review. Eur. J. Nutr. 61:605–613. https://doi.org/10.1007/s00394-021-02665-2

Kunyaboon, S., K. Thumanu, J. W. Park, C. Khongla, and J. Yongsawatdigul. 2021. Evaluation of lipid oxidation, volatile compounds and vibrational spectroscopy of silver carp (*Hypophthalmichthys molitrix*) during ice storage as related to the quality of its washed mince. Foods 10:495. https://doi.org/10.3390/foods10030495

Kwon, H. N., and C. B. Choi. 2018. Comparison of free amino acids, anserine, and carnosine contents of beef according to the country of origin and marbling score. Journal of the Korean Society of Food Science and Nutrition 47:357–362.

Laidlaw, S. A., M. Grosvenor, and J. D. Kopple. 1990. The taurine content of common foodstuffs. JPEN.-Parenter. Enter. 14:183–188. https://doi.org/10.1177/0148607190014002183

Leroy, F., N. W. Smith, A. T. Adesogan, T. Beal, L. Iannotti, P. J. Moughan, and N. Mann. 2023. The role of meat in the human diet: Evolutionary aspects and nutritional value. Animal Frontiers 13:11–18. https://doi.org/10.1093/af/vfac093

Madhu, M., D. Kumar, R. Sirohi, A. Tarafdar, T. Dhewa, R. E. Aluko, P. C. Badgujar, and M. K. Awasthi. 2022. Bioactive peptides from meat: Current status on production, biological activity, safety, and regulatory framework. Chemosphere 307:135650. https://doi.org/10.1016/j.chemosphere.2022.135650

Mahmoud, A., M. Abuelazm, A. A. S. Ahmed, H. Abdalshafy, B. Abdelazeem, and J. R. Brašić. 2022. Efficacy and safety of polaprezinc-based therapy versus the standard triple therapy for *Helicobacter pylori* eradication: A systematic review and meta-analysis of randomized controlled trials. Nutrients 14:4126. https://doi.org/10.3390/nu14194126

Marcolini, E., E. Babini, A. Bordoni, M. Di Nunzio, L. Laghi, A. Maczó, G. Picone, E. Szerdahelyi, V. Valli, and F. Capozzi. 2015. Bioaccessibility of the bioactive peptide carnosine during in vitro digestion of cured beef meat. J. Agr. Food Chem. 63:4973–4978. https://doi.org/10.1021/acs.jafc.5b01157

Mateescu, R. G., A. J. Garmyn, M. A. O'Neil, R. G. Tait, Jr., A. Abuzaid, M. S. Mayes, D. J. Garrick, A. L. Van Eenennaam, D. L. VanOverbeke, G. G. Hilton, D. C. Beitz, and J. M. Reecy. 2012. Genetic parameters for carnitine, creatine, creatinine, carnosine, and anserine concentration in *longissimus* muscle and their association with palatability traits in Angus cattle. J. Anim. Sci. 90:4248–4255. https://doi.org/10.2527/jas.2011-5077

Matthews, J. J., M. D. Turner, L. Santos, K. J. Elliott-Sale, and C. Sale. 2023. Carnosine increases insulin-stimulated glucose uptake and reduces methylglyoxal-modified proteins in type-2 diabetic human skeletal muscle cells. Amino Acids 55:413–420. https://doi.org/10.1007/s00726-022-03230-9

Miller, R. K. 2014. Chemical and physical characteristics of meat: Palatability. In: M. Dikeman, and C. Devine, editors, Encyclopedia of Meat Sciences. 2nd ed. Elsevier, London. p. 252–261. https://doi.org/10.1016/B978-0-12-384731-7.00085-4

Miller, R. K. 2023. Chemical and physical characteristics of meat | palatability. In: Reference Module in Food Science. Elsevier.

Min, B., and D. U. Ahn. 2005. Mechanism of lipid peroxidation in meat and meat products-A review. Food Sci. Biotechnol. 14:152–163.

Mora, L., E. Escudero, P. D. Fraser, M.-C. Aristoy, and F. Toldrá. 2014. Proteomic identification of antioxidant peptides from 400 to 2500Da generated in Spanish dry-cured ham contained in a size-exclusion chromatography fraction. Food Res. Int. 56:68–76. https://doi.org/10.1016/j.foodres.2013.12.001

Mora, L., M. A. Sentandreu, and F. Toldrá. 2007. Hydrophilic chromatographic determination of carnosine, anserine, balenine, creatine, and creatinine. J. Agr. Food Chem. 55:4664–4669. https://doi.org/10.1021/jf0703809

Musakhanian, J., J.-D. Rodier, and M. Dave. 2022. Oxidative stability in lipid formulations: A review of the mechanisms, drivers, and inhibitors of oxidation. AAPS PharmSciTech 23:151. https://doi.org/10.1208/s12249-022-02282-0

Park, Y. J., S. L. Volpe, and E. A. Decker. 2005. Quantitation of carnosine in humans plasma after dietary consumption of beef. J. Agr. Food Chem. 53:4736–4739. https://doi.org/10.1021/jf047934h

Peters, V., V. Calabrese, E. Forsberg, N. Volk, T. Fleming, H. Baelde, T. Weigand, C. Thiel, A. Trovato, M. Scuto, S.

Modafferi, and C. P. Schmitt. 2018. Protective actions of anserine under diabetic conditions. Int. J. Mol. Sci. 19:2751. https://doi.org/10.3390/ijms19092751

Prasow, M., P. Domaradzki, A. Litwińczuk, and M. Kowalczyk. 2019. Bioactive compounds in meat and their importance in human nutrition. Medycyna Ogólna i Nauki o Zdrowiu 25:170–180. https://doi.org/10.26444/monz/112261

Purchas, R. W., S. M. Rutherfurd, P. D. Pearce, R. Vather, and B. H. P. Wilkinson. 2004. Concentrations in beef and lamb of taurine, carnosine, coenzyme Q10, and creatine. Meat Sci. 66:629–637. https://doi.org/10.1016/S0309-1740(03)00181-5

Purchas, R. W., and M. Zou. 2008. Composition and quality differences between the *longissimus* and *infraspinatus* muscles for several groups of pasture-finished cattle. Meat Sci. 80:470–479. https://doi.org/10.1016/j.meatsci.2008.01.013

Radzik-Rant, A., W. Rant, G. Sosnowiec, M. Świątek, R. Niżnikowski, and Ż. Szymańska. 2020. The effect of genotype and muscle type on the physico-chemical characteristics and taurine, carnosine and L-carnitine concentration in lamb meat. Arch. Anim. Breed. 63:423–430. https://doi.org/10.5194/aab-63-423-2020

Richie, J. P., Jr., S. Nichenametla, W. Neidig, A. Calcagnotto, J. S. Haley, T. D. Schell, and J. E. Muscat. 2015. Randomized controlled trial of oral glutathione supplementation on body stores of glutathione. Eur. J. Nutr. 54:251–263. https://doi.org/10.1007/s00394-014-0706-z

Schmid, A. 2010. Bioactive substances in meat and meat products. Fleischwirtschaft International 2:127–133.

Solarczyk, P., M. Gołębiewski, J. Slósarz, M. Łukasiewicz, T. Przysucha, and K. Puppel. 2020. Effect of breed on the level of the nutritional and health-promoting quality of semimembranosus muscle in purebred and crossbred bulls. Animals 10:1822. https://doi.org/10.3390/ani10101822

Sottero, B., G. Leonarduzzi, G. Testa, S. Gargiulo, G. Poli, and F. Biasi. 2019. Lipid oxidation derived aldehydes and oxysterols between health and disease. Eur. J. Lipid Sci. Tech. 121:1700047. https://doi.org/10.1002/ejlt.201700047

Thornton, K. J., R. P. Richard, M. J. Colle, M. E. Doumit, M. J. de Veth, C. W. Hunt, and G. K. Murdoch. 2015. Effects of dietary potato by-product and rumen-protected histidine on growth, carcass characteristics and quality attributes of beef. Meat Sci. 107:64–74. https://doi.org/10.1016/j.meatsci.2015.04.009

Tripathi, A. K., A. K. Ray, S. K. Mishra, S. M. Bishen, H. Mishra, and A. Khurana. 2023. Molecular and therapeutic insights of alpha-lipoic acid as a potential molecule for disease prevention. Rev. Bras. Farmacogn. 33:272–287. https://doi.org/10.1007/s43450-023-00370-1

Vongsawasdi, P., and A. Noomhorm. 2014. Bioactive compounds in meat and their functions. In: A. Noomhorm, I. Ahmad, and A. K. Anal, editors, Functional foods and dietary supplements: Processing effects and health benefits. Wiley, Hoboken, NJ. p. 113–138. https://doi.org/10.1002/9781118227800.ch5

Wang, C., Y. Li, C. Pan, J. Chen, W. Jiang, W. Li, X. Zhang, Z. Liao, and X. Yan. 2021. Quantitative analysis of carnosine, anserine, and homocarnosine in skeletal muscle of aquatic species from east China sea. Biochemistry and Biophysics Reports 25:100880. https://doi.org/10.1016/j.bbrep.2020.100880

Wazir, H., S. Y. Chay, W. Z. W. Ibadullah, M. Zarei, N. A. Mustapha, and N. Saari. 2021. Lipid oxidation and protein co-oxidation in ready-to-eat meat products as affected by temperature, antioxidant, and packaging material during 6 months of storage. RSC Adv. 11:38565–38577. https://doi.org/10.1039/D1RA06872E

Wu, G. 2013. Amino acids: Biochemistry and nutrition. CRC Press, Boca Raton, FL. https://doi.org/10.1201/b14661

Wu, G. 2018. Principles of animal nutrition. CRC Press, Boca Raton, FL.

Wu, G. 2020. Important roles of dietary taurine, creatine, carnosine, anserine and 4-hydroxyproline in human nutrition and health. Amino Acids 52:329–360. https://doi.org/10.1007/s00726-020-02823-6

Wu, H., K. H. Bak, G. V. Goran, and N. Tatiyaborworntham. 2022a. Inhibitory mechanisms of polyphenols on heme protein-mediated lipid oxidation in muscle food: New insights and advances. Crit. Rev. Food Sci. https://doi.org/10.1080/10408398.2022.2146654 (in press).

Wu, H., N. Tatiyaborworntham, M. Hajimohammadi, E. A. Decker, M. P. Richards, and I. Undeland. 2022b. Model systems for studying lipid oxidation associated with muscle foods: Methods, challenges, and prospects. Crit. Rev. Food Sci. https://doi.org/10.1080/10408398.2022.2105302 (in press).

Xing, L., R. Liu, S. Cao, W. Zhang, and Z. Guanghong. 2019. Meat protein based bioactive peptides and their potential functional activity: A review. Int. J. Food Sci. Tech. 54:1956–1966. https://doi.org/10.1111/ijfs.14132

Yeum, K.-J., M. Orioli, L. Regazzoni, M. Carini, H. Rasmussen, R. M. Russell, and G. Aldini. 2010. Profiling histidine dipeptides in plasma and urine after ingesting beef, chicken or chicken broth in humans. Amino Acids 38:847–858. https://doi.org/10.1007/s00726-009-0291-2

Zhang, L., W. Duan, Y. Huang, Y. Zhang, B. Sun, D. Pu, Y. Tang, and C. Liu. 2020. Sensory taste properties of chicken (Hy-Line brown) soup as prepared with five different parts of the chicken. Int. J. Food Prop. 23:1804–1824. https://doi.org/10.1080/10942912.2020.1828455

Zhao, W.-S., J.-J. Zhai, Y.-H. Wang, P.-S. Xie, X.-J. Yin, L.-X. Li, and K.-L. Cheng. 2009. Conjugated linoleic acid supplementation enhances antihypertensive effect of ramipril in Chinese patients with obesity-related hypertension. Am. J. Hypertens. 22:680–686. https://doi.org/10.1038/ajh.2009.56

Zięba, R. 2007. Karnozyna–aktywność biologiczna i perspektywy zastosowania w farmakoterapii. Wiadomości Lekarskie 60:73–79.