Postprint: Relationship Between Post-mortem Muscle Antioxidant Capacity and Meat Quality

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Abstract

After animal slaughter, various oxidative reactions continue to occur within muscle. The extent of post-slaughter muscle oxidation is closely related to meat color, water-holding capacity, shelf-life duration, and other quality attributes. Enhancing muscle antioxidant capacity represents one of the important approaches for improving meat quality. This paper primarily elucidates the effects of post-slaughter muscle antioxidant capacity on meat quality and its underlying mechanisms, and briefly discusses measures to enhance muscle antioxidant capacity and improve meat quality, as well as their application prospects.

Full Text

Relationship between Antioxidant Capacity and Meat Quality in Postmortem Muscle

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Abstract: Following animal slaughter, various oxidation reactions continue within muscle tissue. The extent of these postmortem oxidation processes is closely correlated with critical meat quality attributes including color, water-holding capacity, and shelf life. Enhancing muscle antioxidant capacity represents one of the most important approaches for improving meat quality. This review elucidates the effects of postmortem muscle antioxidant capacity on meat quality and the underlying mechanisms, while also discussing strategies for improving antioxidant capacity and meat quality along with their application prospects.

Keywords: redox reaction; antioxidant capacity; meat quality; pig; broiler
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The cell represents a miniature ecosystem encompassing various chemical, physical, and biological reactions, among which redox reactions constitute a fundamental biochemical process. Biological oxidation involves the enzymatic transfer of hydrogen ions and electrons from metabolites to oxygen (O) to form water (H O), primarily providing usable energy for the organism. Reduction reactions convert certain oxidative intermediates from oxidized to reduced states through enzymatic processes. Normal organisms maintain relatively stable internal environments through complex interactions of oxidation-reduction systems. Disruption of this redox balance leads to oxidative damage, reduced immunity, and compromised animal health, while also causing deterioration in meat quality.

1 Oxidation Reactions in Postmortem Muscle

After slaughter, antioxidant enzyme activity declines while oxidation—being entropy-driven—occurs spontaneously, allowing oxidative reactions to continue in postmortem muscle. Due to energy deprivation, antioxidant capacity gradually decreases, making oxidation the dominant process and generating substantial reactive oxygen species (ROS). High ROS concentrations attack cell membranes, causing protein modification and lipid peroxidation, sometimes resulting in DNA strand breaks or apoptosis [1-2]. Thiophosphorylated DNA reacts with hydrogen peroxide (H O) and hydroxyl radicals in vivo, protecting genomic DNA and sensitive enzymes from intracellular oxidative damage [3].

The antioxidant defense system comprises both enzymatic and non-enzymatic protective systems. The enzymatic system includes catalase (CAT), superoxide dismutase (SOD), and glutathione peroxidase (GSH-Px), while the non-enzymatic system consists of vitamin E, vitamin C, carotenoids, uric acid, and other substances. Although antioxidant substances do not disappear immediately after slaughter, their content and activity gradually deplete during postmortem storage. When depletion reaches a point where ROS damage can no longer be effectively mitigated, significant impacts on meat quality occur.

1.1 Antioxidant Substances

The principal antioxidant substances in animal organisms are three key enzymes: SOD, GSH-Px, and CAT. First, SOD is a crucial enzyme for scavenging free radicals, with superoxide radicals as its substrate. Based on structure and catalytic mechanism, SOD is classified into three types: copper-zinc SOD (CuZn-SOD), manganese SOD (Mn-SOD), and iron SOD (Fe-SOD), all of which decompose H O into H O and O [4]. Second, GSH-Px is another important antioxidant enzyme that reduces lipid peroxides (LPO) and H O to alcohols and H O. It also synergizes with vitamin E to prevent lipid peroxidation and protect cell mem-

branes from peroxide damage [5]. Third, CAT is a typical peroxidase widely present in animal cells and tissues, particularly active in the liver. CAT catalyzes H O decomposition into H O and O , eliminating cellular H O and preventing formation of more harmful free radicals [6].

1.2 Oxidation Products

Malondialdehyde (MDA) is a terminal product of lipid oxidation generated through ROS action on polyunsaturated lipids [7-8]. MDA content reflects the degree of membrane lipid and systemic oxidation, making it an important indicator for studying animal antioxidant capacity. MDA can cross-link and polymerize proteins and nucleic acids, destroying their structure and function. Lipid peroxides (LPO) are produced through free radical chain reactions of membrane phospholipids in polyunsaturated fatty acids (PUFA), typically initiated by hydroxyl radicals in cell membranes. This process generates oxygen-functional products such as MDA and 4-hydroxynonenal (4-HNE), causing damage to biological macromolecules [9].

2 Impact of Postmortem Muscle Antioxidant Capacity on Meat Quality

Current meat quality standards primarily include eating quality and technological quality. Eating quality encompasses flavor, color, and tenderness—attributes valued by consumers—while technological quality comprises pH, shear force, antioxidant capacity, drip loss, and water-holding capacity [10-11]. Meat quality formation is largely associated with muscle oxidation levels, which depend on antioxidant substance content and activity post-slaughter. Declining antioxidant substances (SOD, GSH-Px, CAT, etc.) lead to rapid PUFA oxidation, generating harmful substances including oxygen free radicals and lipid peroxidation end-products that trigger excessive oxidation and damage biological membrane structure and function. As the first line of defense, damaged biological membranes affect cell structure and function, causing water loss, increased fragility, and reduced muscle water-holding capacity [12]. Cellular dehydration and shrinkage also deteriorate muscle color, producing a pale appearance [13]. Furthermore, increased lipid peroxidation products accelerate conversion of oxymyoglobin (MbO) to metmyoglobin (MetMb), changing meat color from bright red to dark brown [14], ultimately resulting in oxidative deterioration, shortened shelf life, and reduced tenderness [15].

Muscle antioxidants (CAT, SOD, etc.) effectively inhibit free radical generation and transfer [16-17], reducing oxidation and preventing declines in nutritional value, sensory quality, and tenderness [18], thereby improving meat quality and extending shelf life. Research demonstrates that Iberian pigs exhibit significantly higher muscle CAT activity compared to commercial breeds such as Pietrain, Landrace, and Large White [19], while Large White pigs show significantly lower subcutaneous fat oxidation than intramuscular fat [20]. Elevated

antioxidant content or activity correlates with lower cooking loss and centrifugal water loss rates [21].

3 Measures to Enhance Muscle Antioxidant Capacity and Improve Meat Quality

3.1 Pre-slaughter Measures

Research indicates that dietary antioxidant supplementation during the feeding stage can enhance animal antioxidant capacity, reduce free radical oxidation rates in muscle, protect biological membrane integrity, and improve meat quality [22-23]. Vitamin E, a primary component of the non-enzymatic antioxidant system, comprises tocopherols and other essential fat-soluble vitamins for animal growth and metabolism. By participating in cell membrane structure, vitamin E inhibits membrane oxidation, preserves membrane structure and function, prevents intracellular water loss, and improves muscle tenderness [24]. The trace element selenium enhances immunity [25] and, as a key component of GSH-Px, plays a significant role in scavenging free radicals and protecting membrane integrity. Selenium also synergizes with vitamin E to improve antioxidant capacity [26]. Selenium-enriched probiotics increase GSH-Px activity and selenium content in piglet blood [27], while selenium supplementation improves meat color by increasing redness (a*) and decreasing yellowness (b*) values [28]. Dexamethasone (DEX), an adrenal corticosteroid drug that alleviates acute stress and allergic reactions, significantly increases plasma total antioxidant capacity (T-AOC) and activities of GSH-Px, CAT, and other antioxidant enzymes when injected pre-slaughter, thereby enhancing antioxidant capacity [29].

Non-conventional feed additives such as alfalfa polysaccharides and tea polyphenols also improve antioxidant capacity. Alfalfa polysaccharides effectively increase antioxidant enzyme activity and overall capacity. Experiments show that adding 1,000 mg/kg alfalfa polysaccharides to diets increases total superoxide dismutase (T-SOD) and GSH-Px activities and T-AOC in hen serum while significantly reducing drip loss in male and female thigh muscle [30]. Mulberry leaf polyphenols increase SOD activity while reducing alanine aminotransferase activity and MDA content [31]. Both theaflavins and tea polyphenols scavenge harmful free radicals [32]. Adding 240 U/kg glucose oxidase to weaned piglet diets significantly reduces serum MDA content [33]. Feeding piglets fermented Chinese herbal residues (Astragalus, Angelica, etc.) significantly increases muscle T-AOC at 7 days of age [34]. Supplementing broiler diets with 100 mg/kg chitosan oligosaccharide significantly increases muscle T-AOC and T-SOD and GSH-Px activities while improving a* values in breast and thigh muscle [35]. Additionally, dietary supplementation with quinoa leaf polysaccharides, peony seed oil, and marigold extract all enhance antioxidant capacity and meat quality [36-38].

However, attention must be paid to supplementation ratios. For instance, adding 100 mg/kg vitamin E to broiler diets does not significantly change

SOD activity or T-AOC in serum and breast muscle nor improve meat quality, whereas increasing supplementation to 200 mg/kg significantly elevates SOD activity and T-AOC while reducing serum MDA content, thereby improving meat quality [39-40].

Animal husbandry practices also significantly affect antioxidant capacity and meat quality. Studies show that free-range broilers exhibit significantly higher renal T-AOC than high-density caged birds [41]. Compared to floor rearing, caged broiler production significantly reduces breast muscle pH at 45 minutes post-slaughter and significantly increases thigh muscle b* values. Low stocking density significantly improves liver T-AOC, serum GSH-Px activity, and breast muscle pH compared to high density [42]. Grazing significantly increases SOD and GSH-Px activities and T-AOC in sheep muscle compared to indoor feeding [43]. Similar research demonstrates that Duolang sheep raised on Gobi desert pastures show superior water-holding capacity, higher a* values at 1 day post-slaughter, and greater PUFA content than intensively farmed sheep [44].

3.2 Post-slaughter Processing and Storage Methods

After slaughter, limited substance exchange allows oxidation to proceed relatively unrestrictedly, accelerating meat oxidation and deterioration. Different storage methods affect oxidation rates and meat quality differently. Cold storage is a common preservation method, and various pre-chilling approaches produce different effects on meat quality and storage duration. During pre-chilling, combined (air + water) chilling and water chilling treatments yield significantly higher muscle lightness (L*) values than air chilling at 24 hours post-slaughter, while water chilling produces significantly higher shear force values. Shear force and storage time show a clear negative correlation [45-46].

Retail storage methods also affect oxidation rates and meat quality. Compared to vacuum packaging, modified atmosphere packaging (MAP) of chicken maintains higher MbO and lower MetMb percentages on days 8 and 12, with significantly reduced drip loss rates. Thus, MAP effectively reduces chicken oxidation rates, improves meat quality, and facilitates preservation [47]. Additionally, incorporating ZrSiO -aluminosilicate glass coatings inside packaging or spraying meat surfaces with 0.05 g/dL rosemary extract effectively inhibits lipid oxidation and color deterioration in MAP products during storage [48-49]. Adding natural antioxidants such as chitosan oligosaccharide to stored beef inhibits MetMb formation, thereby improving antioxidant capacity and extending storage time [50].

4 Summary

Postmortem muscle oxidation severely affects eating quality. Appropriate dietary antioxidant supplementation, suitable husbandry practices, and proper post-slaughter processing and storage can effectively reduce postmortem oxidation rates, representing important strategies for improving meat quality and

extending shelf life.

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Note: Figure translations are in progress. See original paper for figures.