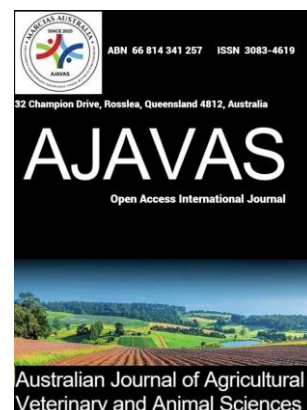




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Review Article

Oxidative stress and its influence on animal health, welfare and productivity

Nathaniel F Ogunkunle ¹ , Emmanuel O Oladejo ² , Michael K Olanrewaju ³ , Onyekachi O Nwankwo ⁴ 

¹ Department of Food and Animal Sciences, Alabama A&M University, Normal AL 35762, USA

² School of Agricultural Sciences and Forestry, Louisiana Tech University, Ruston, LA 71272, USA

³ Department of Animal Science, University of Ibadan, Oyo State, Nigeria

⁴ National Biotechnology Research and Development Agency, Obiense-Ututu, Abia State, Nigeria

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* Corresponding author: nathaniel.ogunku@aamu.edu (Nathaniel Ogunkunle)

ABSTRACT: Oxidative stress is closely linked to inflammation and contributes to the onset of different diseases in farm animals, thereby affecting their health, performance, welfare and productivity. Oxidative damage occurs as a result of the accumulation of free radicals and pro-oxidants that overwhelm the animal's antioxidant defense system. This imbalance impairs growth and reproductive performance, health and welfare, leading to disease susceptibility and reduced productivity. This review highlights the relationship between oxidative stress and inflammation, the production of free radicals, their effect on animal health and welfare, as well as combating oxidative stress with bioactive compounds, minerals and vitamins. Oxidative stress can be prevented through the use of naturally occurring bioactive compounds, vitamins, minerals, appropriate management and production systems. Bioactive compounds and vitamins act by scavenging free radicals through neutralization or by activating the nuclear factor erythroid 2-related factor 2 pathway, which upregulates antioxidant genes and promotes the production of antioxidant enzymes that convert free radicals into less reactive forms. Minerals, on the other hand, serve as co-factors for antioxidant enzymes, thereby enhancing their activity. Additionally, environmental enrichment, animal housing and proper handling can reduce the occurrence of oxidative stress, leading to improved animal health and welfare. In conclusion, oxidative stress can cause significant losses in animal production; however, its prevention through effective management practices and dietary interventions can significantly improve animal health, performance, welfare and productivity.

Keywords: Inflammation; performance; stress; welfare

Highlights

- Oxidative stress is a common phenomenon in livestock production
- Oxidative stress affects animal health, performance, welfare and immunity
- Bioactive compounds, vitamins, and minerals can mitigate oxidative damage

1.0 Introduction

Oxidative stress occurs when there is increased production and accumulation of oxidants accompanied by the body's inability to neutralize them (Kostadinović et al., 2015; Saqib et al., 2023). The accumulation of these free radicals subjects the body to chemical stress, which adversely affects the health of farm animals (Lobo et al., 2010; Ponnampalam et al., 2022). Oxidative stress may also arise from disturbances in endogenous antioxidant balance (Kostadinović et al., 2015), leading to various health disorders (Balmus et al., 2016). Compromised animal immunity increases susceptibility to diseases, resulting in reduced growth and reproductive performance, impaired welfare and diminished quality of animal products.

Optimum animal performance and productivity depend on health and wellbeing, both of which are strongly influenced by oxidative status. Dietary supplementation of antioxidants has been shown to improve animal performance and product quality (Bekhit et al., 2013; Castillo et al., 2013; Salami et al., 2016). A growing trend toward the inclusion of antioxidant-rich compounds in animal diets has been observed in the livestock industry (Iqbal et al., 2022; Oladejo & Ogunkunle, 2024). This is due to the ability of antioxidants to combat oxidative stress which optimizes animal productivity. Plant bioactive compounds, vitamins and minerals have been supplemented to animals because of their antioxidant properties. Vitamins C and E are potent sources of antioxidants due to their hydrophilic and lipophilic characteristics, respectively. Minerals, on the other hand, act as cofactors for antioxidant enzymes, facilitating their activity in neutralizing free radicals (Kruk et al., 2022; Mora et al., 2014). Plant-derived bioactive compounds, including phenolics and flavonoids, contribute to antioxidant defense by scavenging pro-oxidants. Compounds such as quercetin, catechin, apigenin, resveratrol, cannabinoids, lycopene have all been reported to exhibit strong antioxidant properties against pro-oxidants (Ogunkunle et al., 2024a, 2026; Tian et al., 2023; Wu et al., 2024; Zhong et al., 2011).

Jaguezeski et al. (2018) reported the supplementation of curcumin to dairy sheep reduced the occurrence of oxidative damage by increasing the concentration of antioxidant enzymes and anti-inflammatory biomarkers in the blood. Tian et al. (2023) reported that grape pomace extract supplementation alleviated inflammation by reducing IL-1 β , ROS, and MDA in pigs. Similarly, Xun et al. (2021) reported resveratrol to modulate AhR/Nrf2 pathways in weaned piglets. These protective roles were due to the ability of the bioactive compounds to activate the antioxidant defense system which protects the body from oxidative damage and inflammation.

Zhang et al. (2022) also reported vitamin E in alleviating transportation-induced oxidative stress in yaks, with higher glutathione S-transferase in the serum of the animals. Similarly, Jung et al. (2023) reported a supplementation of vitamin E and selenium improved antioxidant status of pregrant dairy heifers up to 3 days post transportation. This review explores the impacts of oxidative stress on animal health, welfare and productivity with the goal of identifying knowledge gaps and provide a basis for further studies on combating oxidative stress in livestock.

2.0 Production of free radicals

Free radicals are by-products of normal cellular metabolism and are characterized as atoms or molecules containing one or more unpaired electrons in their outer shell, enabling them to exist independently (Harper, 2025). These unpaired electrons render free radicals highly unstable, short-lived, and extremely reactive. In their quest to achieve stability, free radicals readily extract electrons from surrounding molecules, thereby converting those molecules into new free radicals. This initiates a chain reaction that can result in extensive cellular damage (Phaniendra et al., 2015). Figure 1 illustrates different sources and production of free radicals in animals.

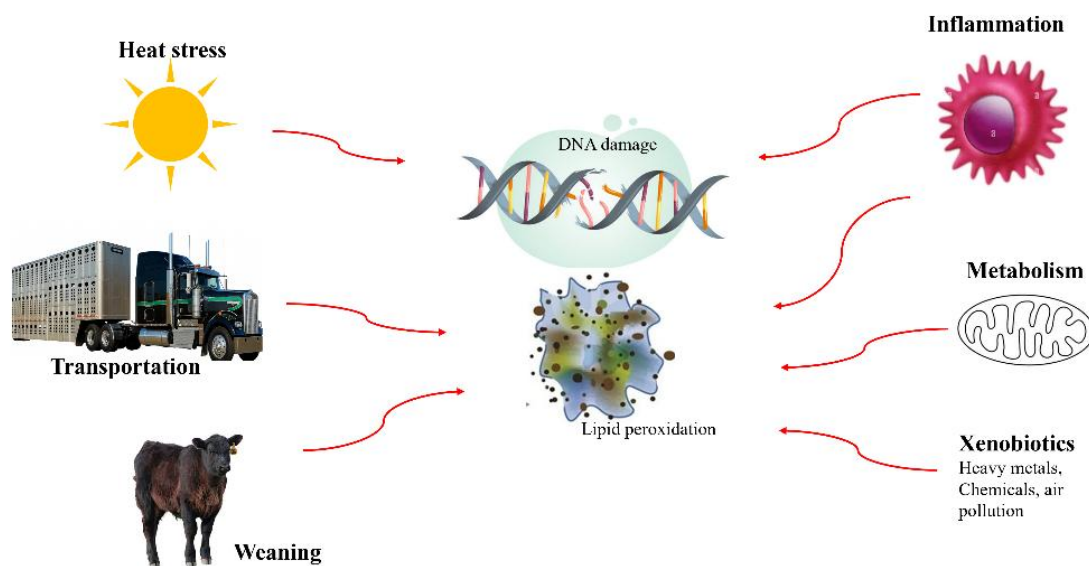


Figure 1. Schematic representation of the major sources of free radical generation in farm animals, including metabolic processes, environmental stressors, and management-related factors

2.1. Mechanism of free radical formation

Free radicals can be generated from both endogenous and exogenous sources (Figure 1). Understanding their physiological mechanisms and their functional role in animal health could prevent the occurrence of diseases (Chandimali et al., 2025; Lobo et al., 2010). Mitochondrial electron transport chain is the major source of endogenous free radical production (Phaniendra et al., 2015). Superoxide radicals are generated when electrons leak and react with molecular oxygen, which occurs during cellular respiration. Apart from respiration, oxidase enzymes such as nicotinamide adenine dinucleotide phosphate (NADPH) oxidase are another source of endogenous mechanism that produces free radicals. This enzyme is found in neutrophils and macrophages, playing an important function in immune response (Panday et al., 2015). NADPH oxidase transfer electrons from NADPH to oxygen, leading to the production of superoxide radicals which is critical for pathogen destruction (Desforjes et al., 2016; Panday et al., 2015). Purine metabolism can likewise generate hydrogen peroxide and superoxide as byproducts by the action of xanthine oxidase (Ma et al., 2018). Superoxide radicals could also be generated from biotransformation of xenobiotics, although the enzymatic activities play an important role in reducing free radicals in the body (Tumilaar et al., 2024). Conversely, the metabolism of xenobiotics by cytochrome P450 can create superoxide radicals when electrons are leaked, potentially reacting with oxygen to produce superoxides (Lismont et al., 2019; Veith & Moorthy, 2018). The end-product of lipid peroxidation, including malondialdehyde and 4-hydroxynonenal, are reactive species capable of inducing oxidative damage to the body (Barrera et al., 2018). Peroxidation of lipids is initiated when free radical removes a hydrogen

atom from polyunsaturated fatty acid (PUFA) leading to the formation of lipid radical, which reacts with molecular oxygen to generate peroxy radical. Peroxy radicals initiate chain reaction of removing hydrogen atoms from lipids thereby generating more lipid and peroxy radicals (Ayala et al., 2014).

Exogenous sources of pro-oxidants and free radical formation are mainly from management practices such as weaning and transportation (Peng et al., 2023; Piccione et al., 2013), heat stress (Alberghina et al., 2024; Montilla et al., 2014), environmental pollutants and toxins such as chemicals and heavy metals (Phaniendra et al., 2015). For example, smoke generated from burning contains a complex mixture of free radicals and pro-oxidants which can be both short and long-lived radicals such as superoxide and nitric oxide. The radicals initiate lipid peroxidation when they penetrate the tissues thereby causing oxidative stress (Caliri et al., 2021). Heavy metal contamination in soil, forages, and water can generate reactive oxygen species (ROS) when consumed by livestock, deplete cellular antioxidants, and expose them to oxidative damage (Bhattacharyya et al., 2014). Free radicals are harmless when produced at low to moderate levels in farm animals, however, they become harmful when they accumulate at higher levels causing cellular damage (Ponnampalam et al., 2022).

2.2. *Types of free radicals*

Free radicals are majorly classified into reactive oxygen species (ROS) and reactive nitrogen species (RNS) (Phaniendra et al., 2015). Reactive oxygen species consist of both oxygen radicals and some non-radicals, which act as oxidizing agents and can transform into radicals (Tashla et al., 2021). These are highly reactive atoms or molecules having one or more than one unpaired electron such as superoxide radical, hydroxyl and peroxy radicals (Martemucci et al., 2022). Free radicals are formed when chemical bonds are broken during reactions. Once formed, they can bind to and damage tissues and biological compounds such as carbohydrates and proteins (Ahmadinejad et al., 2017). Reactive oxygen species are constantly generated during normal metabolism in tissues. During ATP production, oxygen is utilized in mitochondria and water is formed by the reduction of oxygen, however, oxygen intermediate compounds are formed when some quantities are not reduced completely (Tumilaar et al., 2024).

Reactive nitrogen species such as nitric oxide and nitrogen dioxide as well as reactive chlorine species are generated during metabolism (Phaniendra et al., 2015). These oxidants cause damage to biological systems compromising the health of animals, leading to production losses. Nitric oxide plays important roles in vascular regulation, neurotransmission, and immune responses (Di Meo et al., 2016). However, excessive production can lead to its reaction with superoxide to form peroxynitrite which acts as an oxidizing and nitrating agent (Chandimali et al., 2025). Peroxynitrite can modify proteins by oxidizing or nitrating tyrosine residues, ultimately disrupting their function and interfering with cellular signaling pathways (Radi, 2013).

Research relating to oxidative stress is increasing in animal science and veterinary fields because of their connection to numerous diseases. In recent times, most studies have focused on the oxidant and antioxidant status in dairy and beef cattle at different physiological states to combat the detrimental effects of pro-oxidants and to minimize production losses (Abuelo et al., 2015).

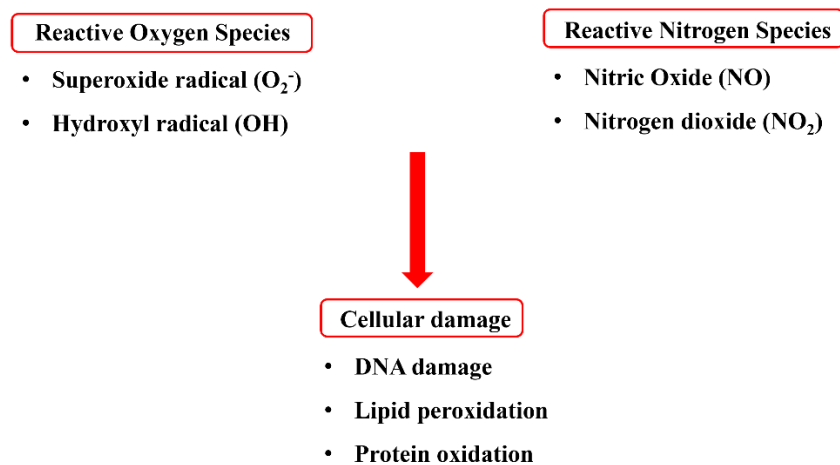


Figure 2. Types of free radicals and their attributes

3.0 Effect of oxidative stress on animal health

3.1. Onset of diseases and immune suppression

The complex mechanism of the immune system helps in protecting the host from pathogenic invasions, but some factors affect its proper functioning (Lacetera, 2012). Researchers have reported heat and oxidative stress affects the immune system in farm animals (Cartwright et al., 2021; Chen et al., 2024). The impact of stress-related events on immune function varies based on the duration of exposure, physiological state of the animal, acclimation level and animal related factors including age, breed, genetics and sex. Animal immunity suppression can lead to increased infections, affecting reproductive and production efficiency, and potentially compromising animal welfare (Lacetera, 2012). This can increase the use of antimicrobials to promote animal health and wellbeing and ultimately causing more antimicrobial resistance.

Chronic exposure to heat stress was reported to impair immune response in animals. Lacetera et al. (2005) described the role of heat stress in impairing lymphocyte function in dairy cows, leading to the reduction in drug and vaccine efficacy and making the animal vulnerable to diseases. Similarly, Lecchi et al. (2016) reported that high temperatures affected neutrophil function. Neutrophils have a protective role in preventing animals against infections. A 2-year study by Vitali et al. (2009) in Italian dairy farms reported a higher mastitis diagnosis in the summer due to heat stress. The risk of immune cell dysfunction in hot environment underscores the importance of management strategies such as evaporative cooling, modified nutritional programs, and enhanced animal hygiene (Oliveira et al., 2025). These practices help regulate body temperature, reducing the likelihood of disease.

3.2. Inflammation

Inflammation is a defensive mechanism used by animals to combat pathogens, resulting in the immune cells producing ROS. These ROS produced during inflammatory response helps to prevent tissue invasion by bacteria, however, prolong production of ROS leads to oxidative stress and inflammatory-associated diseases (Chatterjee, 2016). Excess production of ROS can lead to inflammation by the activation of the nuclear factor kappa B (NF- κ B) which triggers the

release of pro-inflammatory biomarkers such as tumor necrosis factor-alpha (TNF- α), interleukin 1 β (IL-1 β) and interleukin 6 (IL-6). These biomarkers play a significant role in the inflammatory process leading to various chronic diseases (Hussain et al., 2016). The cytokines and chemokines released during inflammation binds to their respective receptors, this also leads to the generation of ROS (Chapple, 1997; Ferrara et al., 2003). The process of inflammation also upregulates inflammatory molecules such as vascular cell adhesion molecule-1 (VCAM-1) and intercellular adhesion molecule-1 (ICAM-1) which mediates the binding of immune cells to endothelial cells, and other immune cells, thereby facilitating their movement into tissues to combat inflammation ((Bui et al., 2020; Verstrepen & Beyaert, 2014). In a study by Chen et al. (2024), the authors reported the upregulation of NF- κ B inflammatory pathway, leading to the production of high pro-inflammatory biomarkers such as IL-6, TNF- α , and interferon gamma (INF- γ) and a significant decrease in anti-inflammatory IL-4 in the spleen in heat stressed chicken. The high pro-inflammatory biomarkers can affect animal welfare and health due to impaired immune function.

4.0 Factors contributing to oxidative stress

4.1. Environmental factors

Climate is one of several factors capable of influencing disease dynamics and is projected to have a profound negative impact on both human and animal health (Rabinowitz & Conti, 2013). Some studies suggests that rising temperatures can lead to a decline in mortality rates and improve the health and welfare of humans and livestock residing in regions with cold winters (Ballester et al., 2011; Rose et al., 2015). Climate change is affecting animal health by the constant rise in temperatures during summer and extremely cold temperatures in the winter.

The role of heat stress in triggering oxidative stress in farm animals has gained increasing attention (Akbarian et al., 2016). Research indicates that serum total antioxidant levels in heifers are lower during the summer than in winter, particularly in peri- and postpartum periods (Mirzad et al., 2018). Similarly, mid-lactating cows exhibit elevated plasma concentrations of reactive oxygen metabolites during hot weather conditions. Studies on different animal species have reported an imbalance between oxidant and antioxidant molecules in the bloodstream during summer (Alberghina et al., 2024; Sumanu et al., 2023; Tang et al., 2022). Heat stress can elevate antioxidant enzyme activity as a compensatory response to heightened ROS production. Additionally, reduced feed intake combined with increased energy expenditure for thermoregulation disrupts energy balance, contributing to weight loss in heat-stressed animals. In a study by Altan et al. (2003), the authors reported the impact of heat stress in 2 broiler strains. Exposure to heat stress resulted in elevated rectal temperature and MDA concentration with reduced SOD, GPx and CAT. Similar observation was reported by Tang et al. (2022), there was lower hepatic MDA and SOD levels, as well as Nrf2 protein, and NQO1 mRNA expressions in the liver of heat stressed broiler chickens. In pigs, Cui et al. (2016) observed upregulation of genes responsible for producing antioxidant defense proteins such as such as PARK7 gene which encodes DJ-1 protein, and GSTM2 gene which encodes glutathione S-transferase. These genes were upregulated in the liver of pigs exposed to heat stress, while acting as antioxidant to protect cells from damage caused by free radicals and other harmful molecules. In another study of pig skeletal muscle from heat stressed pigs, Montilla et al. (2014) highlighted a 2.5 folds increase in MDA after 1 day exposure to heat stress with increased CAT and SOD-1 gene expression in the animals.

The summer season is marked by higher mortality risk for animals, leading to an increase in their death rate (Vitali et al., 2015). Researchers have reported the harmful effects of extreme temperature leading to mortality in farm animals (Godde et al., 2021; Thornton et al., 2021).

Similarly, cold stress plays a significant factor in livestock mortality, leading to considerable economic losses, particularly during winter months (Hu et al., 2021). Cold stress can be categorized as either acute or chronic, depending on its severity and duration (Zhao et al., 2020). Even prolonged exposure to mild cold conditions has been shown to alter digestive function in animals (Muzzo et al., 2024; Wang, Li, et al., 2023). Strong winter winds and snowfall exacerbate heat loss, intensifying cold stress in cattle. Cold exposure also increases gastrointestinal contractions, accelerating feed passage through the digestive tract. As a result, gut microbes and digestive enzymes function less efficiently, leading to incomplete digestion and reduced nutrient absorption (Karl et al., 2018; Wang, Li, et al., 2023). Berian et al. (2019) reported that lactating cows exposed to cold stress showed a decrease in milk yield compared to those in the control group. Similarly, research by Sahib et al. (2024) found that dairy cows subjected to cold temperatures experienced an average of 12% reduction in milk production, primarily due to increased energy demands for thermoregulation. In beef cattle, steers exposed to cold stress exhibited a marked decline in average daily gain, along with elevated physiological stress markers, highlighting the long-term impact of cold stress on beef production systems (Cantalapiedra-Hijar et al., 2018; Lees et al., 2019). Both heat and cold stress present major challenges to livestock health and productivity, underscoring the need for adaptive management strategies to mitigate climate-related impacts on animal agriculture.

4.2. *Livestock production-related factors*

4.2.1. *Weaning*

Weaning is an integral component of cow-calf beef production systems, characterized by separating calves around 6 – 7 months of age from their dams. Weaning is very stressful to both cows and calves (Vogt et al., 2024), it reduces growth performance, and elicits marked behavioral responses, including increased vocalizations which is indicative of compromised animal welfare (Wiese et al., 2016). Calves must adapt to sudden physio-social changes, seasonal climatic changes, new pens at weaning, and dietary changes due to loss of access to udder and milk (Enríquez et al., 2011). These multiple stressors at weaning can lead to loss of body weight, increased body temperature, aggressive behavior, and elevated inflammatory responses due to accumulation of free radicals in calves (Wiese et al., 2016). Several strategies to minimize weaning stress have been reported such as the two-stage weaning method, which was reported to minimize stress response in beef calves. The two-stage weaning method which involves weaning calves from milk before weaning from the dam, was reported to minimize the stress response of beef calves when compared to the traditional abrupt weaning method (Alvez et al., 2016; Ungerfeld et al., 2016). Regardless of the weaning strategy, increased vocalization, aggressive behavior, and elevated concentrations of stress biomarkers including cortisol and ROS were reported (Lynch et al., 2010). This highlighted the adverse effects of the weaning process in animals, which can reduce growth performance during the stocker or feedlot phase.

4.2.2. *Transportation*

Animal transportation is an essential component of the production cycle, occurring during key life events such as sorting, weaning, processing, and slaughter (Schwartzkopf-Genswein & Grandin, 2014). Beef cattle can be transported four or more times during its lifetime; beginning from its birthplace to locations such as an auction, stocker or backgrounding operation, feedlot, and finally slaughterhouse (Deters & Hansen, 2020). However, transportation acts as a significant stressor, predisposing animals to diseases by compromising immune function and increasing inflammation, with limited pre-transport interventions currently implemented (Deters & Hansen, 2020; Van Engen & Coetzee, 2018).

During transit, cattle are exposed to environmental stressors, including free radicals from diesel fumes, which contain organic compounds that can disrupt the mucosal epithelium (Wierzbicka et al., 2014). This exposure may impair respiratory function, increasing susceptibility to respiratory diseases such as bovine respiratory disease (Buckham-Sporer et al., 2023; Riedl & Diaz-Sanchez, 2005). Additionally, loading stress affects both high-temperament and calm-temperament cattle (Burdick et al., 2011). The physical movement during loading and transit elevates the risk of soft tissue injuries, while rough roads and improper handling contribute to carcass bruising, negatively impacting animal welfare and causing economic losses at the processing stage (Huertas et al., 2010; Huertas et al., 2015; Zanardi et al., 2022). Mortality rate was reported to increase with longer transport duration while high temperature-humidity index was also associated with higher mortality during transportation (Lacetera, 2019).

Oxidative stress is another major problem associated with animal transportation (Deters & Hansen, 2020; Li et al., 2024). Animal transportation is characterized by food deprivation, psychological stress, and physical exertion which tend to induce oxidative stress (Deters & Hansen, 2020) through disruption in the balance of ROS in the body. This leads to the buildup of harmful metabolites like MDA while causing significant damage to proteins, DNA, and lipids (Peng et al., 2023). EL-Deeb & El-Bahr (2014) observed elevated plasma MDA levels in buffalo calves following a 4-hour, 250 km transport, accompanied by decreased levels of nitric oxide, SOD, and GPx. Likewise, Wernicki et al. (2014) reported increased serum MDA in beef calves after a 120 km journey. Elevated MDA levels and decreased SOD and GPx in the small intestine of goats subjected to transportation durations of 2 and 6 hours as reported by Peng et al. (2023). Oxidative stress in animals could be related to an increase in ROS induced by transportation. These free radicals generated can induce lipid peroxidation of erythrocyte membranes which is responsible for high MDA levels in transported animals (Xu et al., 2024).

5.0 Combating oxidative stress in animal production

Several antioxidant sources in animal diets help in scavenging free radicals which prevents their accumulation and subsequently the occurrence of oxidative stress. Antioxidants such as polyphenols can neutralize free radicals by donating hydrogen from their hydroxyl group (Chandimali et al., 2025; Lü et al., 2010). Apart from the direct scavenging of free radicals, antioxidants also help in activating the Nrf2 pathway which leads to the upregulation of antioxidant genes to produce more antioxidant enzymes which converts free radicals into their unreactive form (Ma, 2013; Nguyen et al., 2009). The endogenous antioxidant defense system helps in the regulation of free radicals in the body, by catalyzing free radicals into unreactive form. Some well-known endogenous antioxidants include SOD which is present in the cytosol and mitochondria. SOD major antioxidant that catalyzes superoxide radicals into hydrogen peroxide with zinc, copper, and manganese being cofactors. Another major antioxidant is GPx which converts hydrogen peroxide to water through the oxidation of glutathione, and then the oxidized glutathione (GSSG) is reduced back to glutathione (GSH) using NADPH. Furthermore, CAT which is found in peroxisomes and nucleus, converts hydrogen peroxide into water molecules and less reactive oxygen (Jomova et al., 2024). Figure 3 below depicts the mechanism of an endogenous antioxidant defense system with their co-factors.

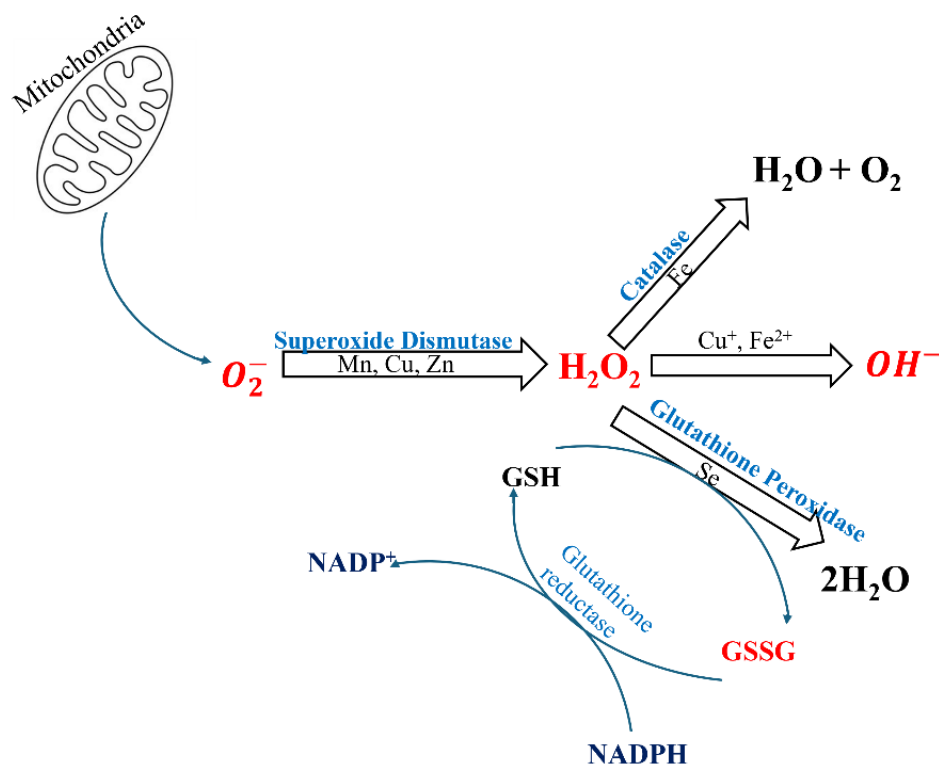


Figure 3. The enzymatic antioxidant defense system and their co-factors

5.1. Supplementation with plant bioactives

There has been consideration in the use of synthetic antioxidants to improve the health, performance and product quality of animals. However, the potential adverse effects (such as endocrine disruption) of the synthetic compounds are limiting their use (Lin et al., 2016). The use of natural antioxidants like polyphenols, flavonoids, and phytochemicals is rapidly being researched in the field of animal nutrition (Ganiyu et al., 2025; Lee et al., 2016). Reports showed that phytochemicals have antioxidant benefits, which favored growth performance and production quality of animals (Lee et al., 2013).

Several natural compounds in plants have been reported to have antioxidant properties (Abbas et al., 2015). Replacing synthetic antioxidants with naturally occurring antioxidants will improve animal performance and health without residual effects on animal products thereby increasing consumer demand for safe animal products (Lee et al., 2016). (Mahfuz et al., 2022) reported medicinal plants have antioxidant properties, which have been used as feed additives in animal production. These bioactive compounds not only promote animal performance, but also improve the quality of animal products and their shelf life. Ogunkunle et al. (2024a, 2026) reported high antioxidant enzyme in the plasma of beef cattle fed industrial hemp-based diet. Industrial hemp was able to combat weaning stress by improving the concentration of GPx and SOD while reducing MDA in beef calves (Ogunkunle et al., 2024b). Similarly, supplementation of industrial hemp to beef heifers reduced oxidative stress biomarkers such as GPx and SOD (Ogunkunle et al., 2024a). In another study, high GPx was reported in the liver of lambs fed chokeberry pomace diet

(Lipińska et al., 2017), and in the plasma of cattle supplemented with green tea polyphenol (Ma et al., 2021). Kafantaris et al. (2017) reported an increase in CAT concentration in lambs fed grape pomace. In poultry, GPx increased with increasing grape pomace supplementation in broilers challenged with coccidiosis (Sharma et al., 2025). Additionally, feeding pigs with grape pomace led to an increase in the expression of Nrf2 and reduction in NF- κ B p65 expression (Horodincu et al., 2025).

Phytochemicals have been extensively documented to modulate inflammatory pathways (Kim et al., 2009), primarily through the downregulation of the NF- κ B pathway (Vafeiadou et al., 2009). Elevated oxidative stress can stimulate the release of proinflammatory cytokines, including TNF- α and IL-6 (Prabhakar, 2013), while simultaneously enhancing the expression of inflammatory mediators such as VCAM-1, ICAM-1, and NF- κ B (Prabhakar, 2013). Polyphenols are capable of interacting with nonpolar compounds located within the hydrophobic inner layer of the plasma membrane. These interactions may influence the oxidative processes affecting lipids and proteins. Certain flavonoids embedded in the hydrophobic core of the membrane can impede the penetration of oxidants, thereby preserving membrane structure and function (Oteiza et al., 2005). Such interactions provide valuable insights into the underlying molecular mechanisms by which polyphenols exert their biological activities, particularly in relation to cellular signaling and transduction processes (Hussain et al., 2016).

5.2. Vitamin and mineral supplementation

Vitamin and mineral supplementation to farm animals have been proven to be effective sources of antioxidants and enzyme co-factors. Water and fat-soluble vitamins are antioxidants that help scavenge free radicals and prevent their accumulation in the body. Vitamin C, a water-soluble antioxidant can protect cells, lipids and proteins from oxidative damage when supplemented at small quantity (Chandimali et al., 2025). It also helps in restoring oxidized form of vitamin E (α -tocopherol) and glutathione (GSSG) to their reduced form, thereby improving their antioxidant status. Lipid soluble vitamin E helps to prevent lipid peroxidation by interfering with lipid radicals which stops its cellular chain reaction. Due to their different subcellular locations, a combination of Vitamin E and C has been shown to have a better antioxidant effect than either of the two vitamins alone (Jena et al., 2013; Ryan et al., 2010).

Injecting goats with vitamin E reduced transportation-induced oxidative stress by increasing the serum GPx concentration, resulting in lower stress in the animals (Danyer et al., 2021). Similarly, injecting vitamin C to yaks improved serum CAT and SOD concentration (Zhang et al., 2023). Administering vitamin E to pregnant cows improved their antioxidative status by significantly increasing the concentration of GPx in the serum of the cows (Yenilmez et al., 2022). Jena et al. (2013) reported that supplementing vitamin E and C to broiler breeder hens during the summer led to higher serum SOD, CAT and lower MDA.

Trace minerals have also been reported to prevent the accumulation of free radicals by scavenging them (Oladejo & Ogunkunle, 2024). Minerals such as zinc (Zn), Manganese (Mn), copper (Cu), selenium (Se), iron (Fe) serve as co-factors of antioxidant enzymes by upregulating antioxidant genes thereby enhancing the production of antioxidant enzymes such as SOD, CAT and GPx as presented in Figure 3. Bicalho et al. (2014) reported increased Cu, Se, and Zn in the serum of dairy cows supplemented with inorganic trace minerals. Similarly, Pogge et al. (2012) reported significantly higher concentration of Zn in the serum and high Cu and Se concentration in the liver of steers supplemented with inorganic trace minerals. Supplementation of complex organic trace minerals to weanling piglets resulted in higher concentrations of Cu/Zn-SOD, Mn-SOD and GPx in the serum (Wang et al., 2023). In another study,

(Xu et al., 2024) reported high total antioxidant, Cu-SOD and GPx enzyme activity in the serum with low MDA in finishing pigs supplemented with organic trace minerals. However, (Trairatapiwan et al., 2025) did not observe any significant difference in SOD activity when low levels of organic trace minerals were fed to broilers.

The negative effect of trace mineral supplementation is mineral toxicity which occurs when animals are fed with high mineral level. Also, Fe^{2+} and Cu^+ can produce free radicals through the Fenton reaction where hydrogen peroxide is converted into hydroxyl radicals which is harmful to the body. Supplementation of adequate level of vitamin and minerals to livestock can boost their immunity by reducing the accumulation of ROS due to the upregulation of Nrf2 and downregulation of NF- κ B pathway to mitigate the adverse effect of stress and inflammation.

5.3. Animal management practices

5.3.1. Environmental enrichment

This involves the introduction of objects (e.g., ropes or balls) or structures (e.g., climbing or elevated platforms) (Gomes et al., 2018) to the animal's surroundings, particularly in enclosed systems, to reduce stress or boredom, encourage exploratory and social behavior, thereby fostering animal welfare. This approach, although species-dependent (Mota-Rojas et al., 2024; Wein et al., 2024), enhances mental, emotional, and physical wellbeing through the decreased production of ROS (Fernandes et al., 2022). According to Herring et al. (2008), environmental enrichment stimulates anti-oxidative defense mechanisms. For example, clinical studies established that environmental enrichment enhance oxidative balance in the central nervous system by decreasing certain oxidative stress biomarkers (da Silva Fidélis et al., 2025; Ramos et al., 2024). Exposure of dry goats to stages and brushes (as enrichment materials) attenuated oxidative stress through decrease in ROS and the oxidative modifications of blood proteins, lipids, and sugars (Wein et al., 2024). Commercial livestock production systems are oftentimes subjected to an intensive, enclosed system. Therefore, the incorporation of environmental enrichment is a promising intervention to promote animal health and welfare by improving overall stress resilience.

Proper ventilation, planting of trees to serve as shades, genetic selection: breeding for animals with better adaptive responses to stressors and stronger innate antioxidant capacities.

5.3.2. Housing and Handling conditions

Poor sanitary conditions, inadequate space, and solitary housing ((Marco-Ramell et al., 2016; Sierżant et al., 2019) have been clearly identified as major risk factors for animals raised under intensive production systems. These factors are linked to oxidative stress, as evidenced by increased blood hydroperoxides and reduced total antioxidant capacity in pigs (Sierżant et al., 2019). For instance, when young pigs were moved from group housing to individual pens, salivary cortisol levels rose, accompanied by elevated blood oxidative stress biomarkers (Marco-Ramell et al., 2016). Similarly, Quesnel et al. (2019) reported that piglets from dams housed on concrete slatted floors had lower blood antioxidant status than those from dams kept on straw. In ewes, the shearing process also increased blood oxidant levels (Fazio et al., 2018).

To prevent these adverse effects, animals should be maintained under consistent and suitable housing conditions throughout their lifetime. Combining favorable rearing environments with proper ventilation and environmental enrichment can enhance animal health, welfare, and productivity (Abo Ghanima et al., 2020). Furthermore, strategies should be developed to minimize the physical, psychological, and behavioral stress associated with livestock handling and production. Establishing an ecosystem that reduces both physical and psychological stressors can help prevent disease transmission and mitigate oxidative stress.

Transportation

Road transport elevates oxidative conditions, raising livestock welfare and economic concerns (Fazio et al., 2018). Strategies must be implemented to minimize the potential injury, fear, or fatigue during transportation (Deters & Hansen, 2020). These strategies may include 1) assessing the physiological state of animals to be transported, ensuring that no indisposed or gestating animal is present. 2) acclimatizing animals to transport equipment early in life to reduce fear or anxiety at an advanced age 3) the use of an environment-controlled transport vehicles would significantly help maintain or promote animal welfare

6.0 Conclusion

Oxidative stress is the culprit in animal production; it affects immunity which exposes animals to several diseases. Understanding different management and environmental factors contributing to oxidative could proffer a sustainable way of improving animal production systems to limit the occurrence of oxidative stress in farm animals. Exploring the significant impact of different bioactive compounds with antioxidant and anti-inflammatory properties in animal production could improve animal performance and productivity during the constantly changing environmental conditions. Preventing the occurrence of oxidative stress through management and dietary interventions can significantly improve animal health, performance, welfare and productivity thereby encouraging sustainability of livestock production.

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