

Oxidative Stress in Ruminants: Nutritional Approaches for Mitigation and Improved Performance: A Review

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Annotation: Oxygenic pressure is a fundamental element of the ruminants health, proliferation and productivity. In excess they refer to disturbance and imbalance in the production of (ROS) and the antioxidant function as a result of cellular and metabolic dysfunctions. Sources of major ROS in ruminants, specifically due to environmental toxicants, nutritional imbalance, or an acute pathological process, particularly during special conditions like pregnancy or lactation, are being pointed out in the present review. Which leads to the weak ability of immunity and reduction of growth, milk yield and fertility, and brings huge economic losses to animal husbandry. In diseases where mitigating oxidant stress is advantageous, dietary manipulations can have an impact. We know the presence of vitamins (E, C, β -carotene), trace elements (selenium, zinc, copper, manganese) and phenolic compounds such as polyphenols, flavonoids and essential oils can contribute enormously to ROS scavenging and therefore possibilities of redox environment bartel2005regulation; dou et al. These are changing due to some new strategies recent on the market in order to ensure high integrative bioavailability of dietary antioxidants applied and long-term protection from oxidative aggression: probiotics, prebiotics and nano-supplements (capsulated formulas). Conclusion The hormonal regimens with spermatogenic protocols can definitely be combined to improve growth, reproductive performance, and immunity for sustainable livestock production. The information obtained from nowadays investigational Ialso emphasized importance of one's diet in relation to

antioxidant diet regimen driven by oxidative strain and suitable barding methods found in ruminants to minimized oxidative pressure. However, other fundamental issues such as combinations and doses optimization, determination of long-term effects and measurement of contribution to sustainability still need to be researched to improve ruminants resistance and performance under OS.

Keywords: Ruminants; Selenium; Zinc; Probiotics; Nano-supplements; Encapsulation; Sustainability.

Introduction

Oxidative stress is a pathological condition characterized by overproduction of ROS over the capacity of antioxidant defense systems to remove them, leading to cellular damages and malfunction (Sies 2018). The Metabolic Background in Ruminants• Endogenous oxidative stress can be derived from the metabolic background (e.g., rumen fermentation process, mitochondrial respiration) or from exogenous factors (heat stress, underfeeding, toxins, environmental pollutants) (Castillo et al., 2013; Chauhan et al., 2014) in ruminants.

ROS are produced in excess and injure lipids, proteins, and nucleic acids, which leads to a loss of health and productivity of an animal. Pro-oxidant and antioxidant are important for maintaining the homeostasis and the physiological condition of all the cells. These compounds include both enzymatic (e.g., superoxide dismutase, glutathione peroxidase and catalase) and non-enzymatic species (vitamins A, C, E), carotenoids and micro-minerals (selenium, zinc) (Lykkesfeldt & Svendsen, 2007; Chauhan et al., 2015) that play an important role in detoxification of ROS and in protecting the ruminant tissues from oxidative injury. . It is a sort of equilibrium that involves not only the preservation of regular metabolic processes but the enhancement of immune activity and reproductive success too. Oxidative stress is a commercially relevant enemy of any animal production system, which is however, currently unknown. This is linked to reduced feed efficiency, low gain rate, low reproduction and high risk of diseases leading to substantial economic losses (Bernabucci et al., 2002; Sordillo & Aitken, 2009). Reduction of milk yield and elevated fertility are not the only effects in dairy cattle, but in small ruminants (sheep and goats), lambing/kidding retention and also weaklings are directly related to oxidative stress with lambs and kids with low birth weights more susceptible to neonatal death (2829). Among them, in Awassi ewes the variation in blood physiological and biochemical profile and its relation with reproductive performance among ewes of different hormonal stage has been described with potential implications on the endocrine control of fertility (Alwan et al., 2018a; 2018b). These discoveries display the harmful influence of oxidative stress on the host animal as a biological target and the farmer as an economic target. Consequently, knowledge of the mechanisms of oxidative stress in ruminants and dietary management to alleviate its adverse impacts are key to the improvement of animal health and performance, while promoting the sustainability of livestock systems.

This paper is aimed to give an insight perspective regarding oxidative stress in ruminants focusing on mechanisms and effects and also the modulatory effect of nutritional strategies on oxidative stress.

Sources and Consequences of Oxidative Stress in Ruminants

Oxidative stress in ruminants is considered as a specific event, where environmental, nutritional and physiological factors combine to disturb the equilibrium between oxidant production and antioxidant defences.

Environmental Factors

A significant contributor to oxidative imbalance in the ruminants is oxidative stress resulting from environmental challenges [8]. Heat stress reveals a metabolic activator, leading to elevated levels of oxygen consumption which in turn develops excess production of reactive oxygen species (ROS) (Bernabucci et al. 2002; Chauhan et al. 2014). Nutritional imbalances such as low energy or protein intake, or feeding systems lacking antioxidant vitamins and minerals will increase oxidative damage by decreasing the endogenous antioxidant capacity available to the animals (Lykkesfeldt & Svendsen, 2007). Additionally, chronic oxidative stress is produced by the ability of mycotoxins in feed substrates to induce lipid peroxidation and consequent impairment of immune mechanism (Kaur et al., 2014).

Physiological Processes

During the ruminant life, certain physiological processes make the animal disposition to oxidative stress. In contrast, pregnancy and lactation should be considered specific metabolic foci because both mitochondrial activity and body reserve mobilization are increased above normal, enabling a further contribution to the mitochondrial ROS production (Castillo et al., 2013). In addition to this development of lamb and kid is quick, and oxidative challenges happen as a result of rapid tissue accretion during this process. Moreover, the immune activation itself such as that induced by infections or vaccination stimulate oxidative bursts that deplete the antioxidant defences (Sordillo & Aitken, 2009).

Consequences for Health and Production

The oxidative stress is a real threat to the health and productivity of animals not only at the cellular level. Detrimental effects of free radicals have been directly related to decreased oocyte quality (Palani, Z. M. R., Ameen & Shekhani, 2025), sperm malformation and lower conception rate leading to impaired reproductive performance due to oxidative stress. In a nutshell, oxidative stress has a negative association on milk production and milk quality (below) for dairy ruminants (Chauhan et al., 2015), while on the other hand, it leads to a decrease in growth performance and carcass traits for meat ruminants (Chauhan et al., 2015). Persistent oxidative stress causes immunological suppression so infectious diseases are less vigorously countered and hence greater morbidity and mortality ensue. Taken individually, such responses are equivalent to large economic losses (Sordillo and Aitken, 2009) to either smallholder or intensive production systems. For that reason, oxidative stress is a health and economic menace in ruminants. A viewpoint of the multifaceted etiology and effects is warranted, to best-fittingly optimize nutritional and administration techniques to permit for reliable manufacturing overall performance of the animals, as properly as their health.

Nutritional Antioxidants in Ruminant Diets

It has been shown that carefully supplementation of dietary antioxidants may reduce the oxidative stress in ruminants to a great extent. These antioxidants are able to counteract such oxidative stress by maintaining redox homeostasis and create a healthy and productive milieu. Dietary antioxidants can be grouped into three broad categories: vitamins, trace minerals, and plant-derived bioactive compounds.

Vitamins

Vitamin E is the most powerful vitamin among lipophilic antioxidants. Such protects membrane polyunsaturated fatty acids against lipid peroxidation and has been linked to reduced mastitis development, enhanced immune status, and better quality of meat and milk (Chauhan et al., 2014). But, whilst vitamin C is produced in a ruminant's body it is only conditionally essential in negative conditions like heat stress or during infection. It scavenges ROS and recycles oxidized vitamin E as a result enhances antioxidant network (Lykkesfeldt & Svendsen, 2007). Provitamin

A, like β -carotene, has an antioxidant effect and stimulates reproductive performance (Arechiga et al., 1998), compensating oocyte quality, luteal activity, and fertility in ruminants.

Trace Minerals

Cofactors for enzymatic antioxidants: enzymes of the body antioxidant defence mechanism. Selenium (Se) Selenium is an essential part of glutathione peroxidase, an enzyme protein that helps remove hydrogen peroxide and lipid peroxides. Moreover, other experiments conducted in Kudi sheep indicated that selenium supplementation markedly improved antioxidant indices and mitigated the risk of oxidative stress mediated potential by lowering different pathophysiological indices induced by oxidative stress (Palani et al., 2024a). AbstractObjectiveZinc (Zn) has an important structural and catalytic role in superoxide dismutase (SOD) and immunocompetence. Besides direct effect showed on antioxidant functions, however, some improvement in reproductive traits and testicular parameters is indirectly reflecting improvement of antioxidant functions by zinc. Furthermore, copper (Cu) and manganese (Mn) are cofactors or coenzymes of SOD enzymes essential for protecting tissues from oxidative defenses and improving metabolic reactions and regulation (Spears & Weiss, 2008).

Plant-Derived Bioactive Compounds

This nutrient inhibits the absorption of antioxidants found in plants, such as polyphenols, flavonoids, and essential oils, under dense, silent protection and protection. These plant chemicals inhibit free radicals, modulate rumen fermentation, and alter the balance of gut microbes. Recently, products made from saffron (*Crocus sativus*), a compound rich in crocins and highly effective in antioxidants, have shown positive effects on metabolism due to their potent antioxidant properties (Mohammed, Balani, & Al-Zubaidi, 2025). These bioactive compounds also shown to enhance oxidative stability of milk, reduce methane emissions and enhance immune response therefore providing dual beneficial effects on health and environment (Chauhan et al., 2015). Flavonoids are widely known to be associated with better reproductive performance (Surai, 2016) and stress coping ability (Surai, 2016) in poultry, and vessels health (Surai, 2016) as well, either of these factors has direct impact on egg quality, so legumes and herbs are the some of the richest sources of flavonoids as well.

A synergistic network of vitamins, minerals and phytochemicals acting as antioxidants. They are involved in feeding strategies due to the necessity of enhancing animal health, such as ruminant reproduction and products quality but also associated with the impacted production systems.

Nutritional Strategies for Mitigation

Dietary treatment is the direct and one of the most effective method of combating oxidative stress in ruminants. Novel nutritional strategies include but are not limited to natural feed additive, probiotics and prebiotics, and nanotechnology-based supplementation (i.e., nano-supplement or encapsulation) pathways in both companion and farm animals aside from classical antioxidant vitamins and minerals. These strategies, along with advances in aquaculture efficiency and sustainability, will work to enhance the antioxidant defense system. Plant products (such as herbs, plant extracts, and essential oils) contain plant secondary metabolites such as polyphenols, flavonoids, and terpenoids, which possess potent antioxidant and immunomodulatory activities. Plant extracts (rosemary, turmeric, saffron, etc.) are potent free radical scavengers and protect cells from oxidative stress (Mohamed et al., 2012). Many essential oils, such as thyme, oregano, and clove, are important and important sources of antioxidants, but their antimicrobial and functional activity influence fermentation within the rumen environment (Chauhan et al., 2015). These naturally derived compounds have a dual effect: they improve overall animal health and reduce the use of synthetic feed additives, reducing toxicity and costs—a global trend in environmentally sustainable animal production for the future.

Probiotics and Prebiotics

The introduction of essential and important microorganisms (live lactobacilli, mycoplasma, albicans, and saccharomyces) and prebiotics (non-digestible sugars that can stimulate the proliferation and reproduction of bacteria) is of great importance and essential in modulating oxidative stress. Moreover, by enhancing gut health and immunity, they also indirectly alleviate metabolic oxidative stress, and improve the bioavailability of substrates in companion animals and livestock (Patra & Yu, 2015). In addition to the observed results, several probiotic studies in ruminants have reported an enhancement in antioxidant enzyme activity and decrease in lipid peroxidation whereas prebiotics have reported ruminal fermentation advantages along with significant immune responses under stress conditions (Kaur & Sharma, 2019). Therefore, these functional additives can effectively offer biocompatible intervention to alleviate oxidative stress in an efficient manner and free of drug residue and other detrimental environmental concerns.

Advanced Technologies: Nano-Supplements and Encapsulation

Recent Innovations in Feed Technology for Improving Bioavailability of Feed Antioxidants through Use of Nano-Nutraceuticals and Nanoencapsulation Providing supplements of nano-selenium and nano-zinc with much higher bioavailability and localization than normal supplementary forms. Nano-selenium obtained higher GSH-Px activity than different positive inorganic selenium species in terms of reproductive and stress tolerance characters in selective small ruminants environments (Selim et al., 2020). Especially with regard to potentially ruminal degradable antioxidant sensitive substances (vit. E or essential oils) reaches a slow-release effect in the intestine and therefore a further increase in the systemic antioxidant capacity (Gallo et al., 2018). The above glue together the integrated technology advances in a synergy with precision nutrition and sustainable ruminant production systems. Altogether, these dietary changes (natural feed additives, microbial manipulations and technological innovations) embody a multifactorial approach to combat oxidative stress. Their combined usage could improve animal health and productivity and reduce economic losses due to oxidative disbalance in ruminant production units.

Impacts on Animal Health and Performance

Innovative feed and management strategies in oxidative stress control will pay huge dividends in ruminant health and performance. These are all associated with redox homeostasis that, if targeted, could lead to enhanced growth and reproduction, disease resistance, and both short- and long-term profitability and sustainability of the farms. Growth and Milk Production: Nutritional imbalances generate enough oxidative stress that affects both nutrient utilization and energy partitioning which ultimately results in reduced growth rate and low milk production. From various studies [6, 32]–[34], the supplementation of antioxidants [vitamin E (α -tocopherol, α -TOC), selenium, and zinc] at the ratio has been observed to positively affect average daily gain, gain: feed and carcass characteristics per se in growing lambs and goats, respectively. An impressive elevation in antioxidant status will also reduce the oxidative insult of mammary tissues in dairy animals resulting in an increase in both milk quantity and quality namely, the shelf life of fat in milk (Bernabucci et al., 2002). Nano-supplemented Se and EO- encapsulated also reported higher bioavailability and thus it may also improve lactation performances 2,5 through heat stress or under super high production conditions (Selim et al.

Immune Enhancement and Disease Reduction

Increase in oxidative stress diminishes immune-cell activity and renders the animals vulnerable to infection and inflammatory illnesses. Due to their systemic effect, diets supplemented with anti-oxidants may therefore serve to redistribute neutrophils to their place of activity where they may mitigate the frequency of mastitis, pneumonia and gastrointestinal disease (Sordillo & Aitken, 2009). The minerals and vitamins selenium and vitamin E have strong beneficial effects to enhance immune function and also to reduce pathogen mediated morbidity due to their potent

antioxidants regulating glutathione peroxidase activities in the body (Palani et al. 2024b). Furthermore, many plant extracts and probiotics have affected the gut microflora and subsequently reduced the systemic immune suppression and consequently increased the host immunity (Patra & Yu, 2015).

Sustainability and Economic Benefits

From an economic viewpoint, the use of antioxidant feeding strategies provides disease protection and ensures minimization of oxidative stress related production and mortality costly losses. Both of these traits lead to the reduced calving/lambing intervals, which both shows the attachment with the overall profits of the herd (Palani et al., 2025; Ameen & Shekhani, 2025). This is because, encapsulated formulations of phytogenic feed additives are more compatible with the human requirements of animal production system with minimized organ level as well as tissue deposition and residues (Mhamad & Palani, 2025) by which, can help in increasing the competitiveness of ruminants production system. The decreasing of oxidative stress (OS) relates to animal welfare (AW), which is one key factor intersects environmental science and sustainable food production system approaches.

Conclusion

Despite this, oxidative stress can be present in ruminant production systems due to environmental challenges, nutritional deficits and the high physiological demand of reproduction or lactation. This perspective clearly demonstrated the significance of nutritional antioxidants from vitamins (E, C, and β -carotene), trace elements (selenium: Se or zinc: Zn; copper: Cu, and manganese: Mn), and phytogenic metabolites in the amelioration of oxidative stress and redox balance. Some of the above interventions generally indirectly enhance animal health, in addition to: reducing antioxidant defense strategies, altering growth performance and efficiency, reproductive and reproductive efficiency, and immunity (with current approaches, probiotics, prebiotics, nano-supplements, and encapsulation strategies). All of these additives work across different stages of the food chain in a way that can significantly reduce the economic losses caused by the use of livestock systems while increasing production efficiency. This leads to, and thus, helps shape the sustainable stick in a sustainable food chain in which animal agriculture will have to play a role (again).

Future Directions and Recommendations

Still, as with the fourth paragraph above, progress, at least, is still progress. Stress type (common/cultural) Dose response relationship on/out of usual time series of plants in response to suitable dose of Oxidative stress. Further studies must be expected on Effects of antioxidant characteristics (independent) and with other environmental stresses like heat/ disease etc. Vit-Mix synergism in the antioxidative defense — a synergy of vitamins, minerals and phytogenics? Examine the (chronic) effects of new technology nano-supplements and encapsulated antioxidants on animal health, reproduction and product quality. Broaden this research to include small ruminants (sheep and goats) which arguably have been afforded less attention compared to dairy cattle, yet are key animals for many arid and semi-arid environments. Sustainability assessment for ecological and economic benefits from climate-smart and global-relevant-sustenance nutrition-based antioxidant strategies. By overcoming these issues, this could allow for a stronger scientific foundation for the development of sustainable and economical feeding strategies, that will enhance the productivity and health of e.g. ruminants exposed to oxidative stress in the future.

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