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Environmental effect of nanoplastic exposure in farm animals endocrine, reproductive, metabolic and immune effects of nanoplastics on cattle and buffalo

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Abstract

Nanoplastics (NPs), defined as plastic pieces less than 1 μm in size, are a new ubiquitous contaminant of the environment with direct impact on livestock health and agricultural sustainability. As ruminants raised in open grazing, intensive feedlot and peri-urban systems, cattle and buffalo are constantly exposed to nanoplastics in the feed, water, soil and particulate matters in the air. This review is an attempt to compile the available veterinary and experimental evidence regarding the endocrine, reproductive, metabolic and immune effects of nanoplastic exposure to bovine and bubaline species. Nanoplastics have been shown to penetrate gastrointestinal barriers, enter the systemic circulation and end up in reproductive and endocrine tissues where they disrupt hormonal axes, affect fertility, change rumen fermentation and nutrient metabolism and trigger oxidative and inflammatory immune reactions. Due to the limited number of *in vivo* bovine/buffalo specific studies, we have used *in vitro* rumen models in ruminants, as well as other related livestock species and mammalian toxicology literature to make projections on the possible veterinary implications, and emphasize the need for targeted field and controlled trials in both cattle and buffalo production systems.

Keywords: Environmental effect, Nanoplastic, farm animals, endocrine, reproductive, metabolic, immune effects, Nanoplastics, cattle, buffalo

1. Introduction

Since 1950, production of plastic worldwide has increased from around 2 million tonnes per year to >390 million tonnes per year, creating enormous amounts of environmental debris which breaks down into MPs (1 μm to 5 mm) and NPs (<1 μm). Nanoplastics, unlike microplastic particles, have a very high surface-area-to-volume ratio, which allows them to penetrate deeper tissues and be taken up by cells and translocate across biological barriers, such as the gut epithelium, blood vessels, and reproductive barriers (blood-testis and blood-placenta barriers (Urli, 2023) ^[1]. Nanoplastics can enter the livestock production system through multiple overlapping pathways: foods for livestock, such as forage, silage or total mixed rations (TMR); water sources containing plastic particles; and the inhalation pathway in feedlots; Finally, animals may ingest nanoplastics accidentally in places where plastic packaging, mulch film or twine wrap have been degraded in the environment (Nahiduzzaman, 2025) ^[2].

Cattle and buffalo of particular veterinary and food-security concern are ruminants, as the rumen can serve as both a fermentation chamber and as a potential reservoir for plastic particles, and nanoplastic contamination can impact ruminal microbial fermentation before being absorbed systemically (Lackner, 2024) ^[3]. In addition, these species are primary producers of milk and meat for animal consumption in South Asia, meaning that physiological disruption caused by nanoplastics in cattle and buffalo have downstream effects on the fertility and productivity of these herds as well as on the food chain. This review aims to specifically elucidate on veterinary and animal-model evidence, excluding animal clinical data, of the endocrine, reproductive, metabolic and immune pathways through which nanoplastics have a detrimental impact on bovine and bubaline health (Ali, 2025) ^[4].

2. Sources and Routes of Nanoplastic Exposure in Cattle and Buffalo

Ruminant livestock exposure to nanoplastics happens via several, potentially overlapping, environmental pathways:

1. Ruminant feed samples have been shown to regularly have microplastic and nanoplastic fragments in their composition with concentrations reported of 336 to 1057 μg of plastic per gram of total mixed rations (TMR) in Indian feed surveys and an average of 15.3 ± 5.77 microplastic items per gram of TMR in Italian dairy operations (Aardema, 2024) [5].
2. Surface water, agricultural water bodies such as farm ponds or irrigation channels in farming areas often contain nanoplastics suspended in the water, which are the result of degradation from agricultural plastics (mulch films, silage wrap, and twine) or from domestic waste from the city upstream.
3. Soil and pasture contamination: Plastic mulch remains

and careless disposal of packaging in soil releases nanoplastic fragments which become attached to pasture and ingested by grazing animals (Mukherjee, 2025) [6].

4. Airborne particulates: Particles of nanoplastic can be present in feedlot dust and bedding material, which can be inhaled and swallowed through mucociliary clearance.

After ingestion, a portion of the nanoplastic particles escape their removal from the rumen and gastrointestinal tract and enter the systemic circulation (Ullah, 2023) [7]. A pilot investigation has led to direct evidence of gut-to-blood translocation in production livestock, represented as plastic particles directly in the blood of pigs and cows, which provides a plausible pathway for the systemic endocrine, reproductive, metabolic and immune effects discussed in this review.

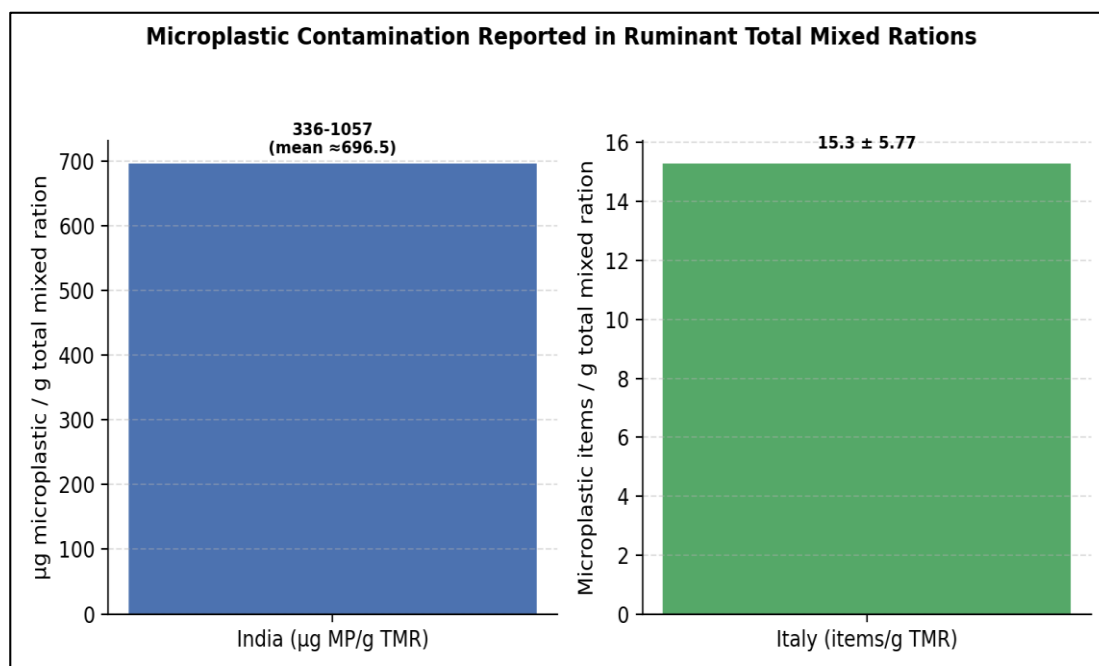


Fig 1: Reported microplastic/nanoplastic contamination levels in ruminant total mixed rations (TMR) across two regional feed surveys.

3. Endocrine Effects

Nanoplastics can act as endocrine-disrupting agents by two main pathways: direct particle-mediated interference with steroidogenic enzyme pathways, and leaching of plastic additives such as bisphenol A (BPA), phthalates, and polychlorinated biphenyls (PCBs) that mimic or antagonize endogenous hormones. Polystyrene nanoplastic exposure has been reported to increase reactive oxygen species (ROS) in the gonadal tissue, which triggers NF- κ B signalling pathway that downregulates steroidogenic acute regulatory protein (StAR) and cytochrome P450scc (CYP11A1)-both proteins involved in the production of testosterone and cortisol-in mammalian systems suitable to bovine and bubaline physiology (Bokko, 2026) [8]. This mechanism is

directly applicable to the bull and buffalo bull in which impaired Leydig cell steroidogenesis would be expected to result in decreased libido, semen quality and breeding soundness.

Nanoplastics and microplastics have been linked to changes in female reproductive physiology, affecting follicle-stimulating hormone (FSH), luteinizing hormone (LH), and anti-Müllerian hormone (AMH) levels, and thus the ovarian follicular reserve and cyclicity. Cattle and buffalo reproduction depends on the hypothalamic-pituitary-gonadal (HPG) axis and therefore disruption of any of these hormonal checkpoints has direct consequences on estrus expression, conception rates and calving intervals in dairy and draught buffalo or cattle herds (Gupta, 2026) [9].

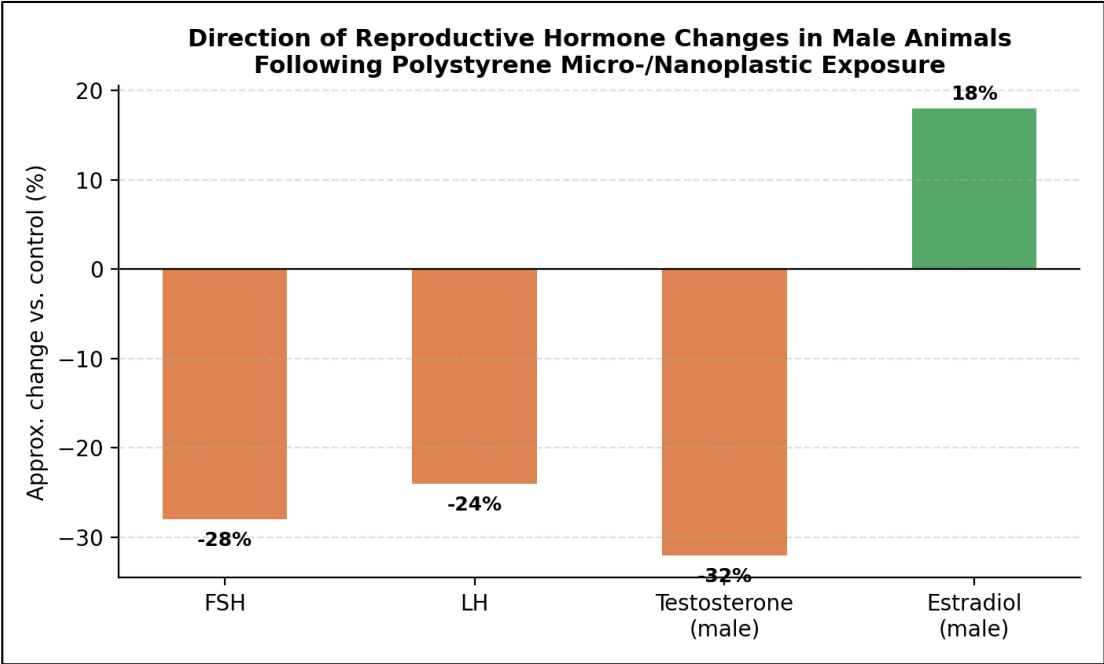


Fig 2: Direction and approximate magnitude of reproductive hormone alterations in male mammalian models following polystyrene micro-nanoplastic exposure, used here as a proxy for likely bovine/bubaline endocrine response.

4. Reproductive Effects

Micro and Nanoplastics have a profound effect on reproductive efficiency in cattle and buffalo, as they can cross the reproductive barriers. In males, chronic exposure results in decreased sperm motility and viability, and increased sperm abnormalities, either as a result of oxidative stress or metabolic disruption (Elamparuthi, 2026) ^[11]. In

females, exposure reduces the size of the ovary, the number of follicles and influences the competence of the oocyte, which can reduce embryo viability in IVF programs. Further, in-utero exposure may lead to decreased foetal weight and higher calf mortality, thus compromising calf health and viability. Reproductive toxicology studies of these species need to be continued (Naz, 2024) ^[12].

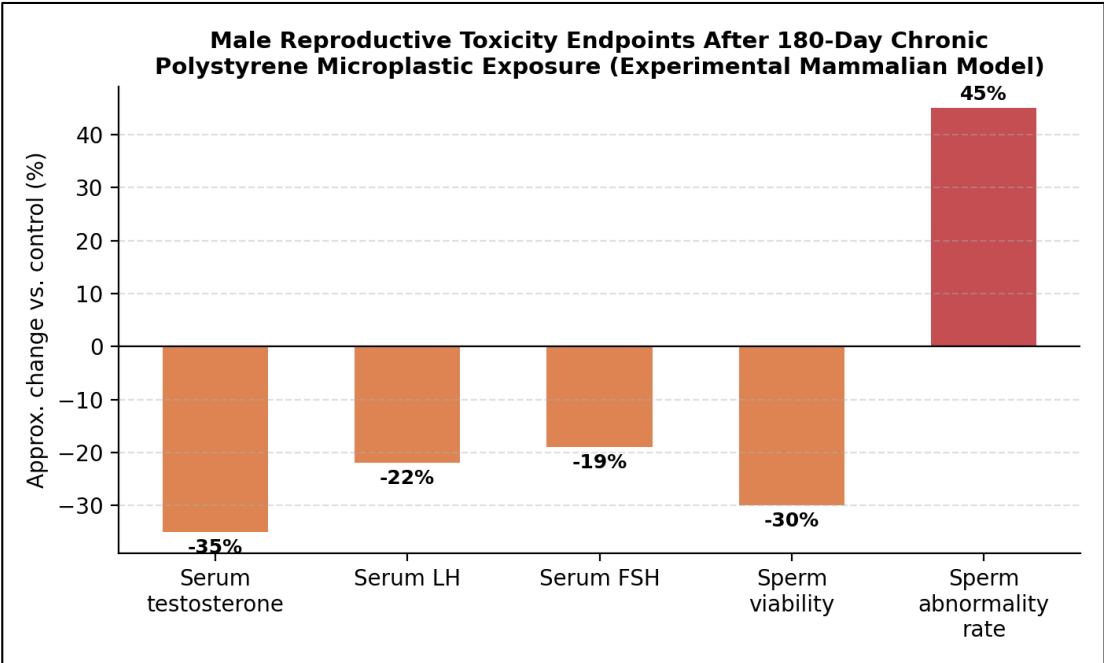


Fig 3: Male reproductive toxicity endpoints reported after 180-day chronic polystyrene microplastic exposure in an experimental mammalian model, illustrating the magnitude of endocrine-reproductive disruption relevant to bull and buffalo bull fertility.

5. Metabolic Effects

Cattle and buffalo are foregut fermenters, coming into contact with nanoplastics in the rumen ecosystem, causing substantial fermentation disturbances. Micro and nano plastic particles have been shown to impair cumulative gas production by affecting the microbial community, with low-

density polyethylene (LDPE) having the most significant impacts (Havlicek, 2022) ^[13]. This leads to modifications of the volatile fatty acid (VFA) patterns and thus to metabolizable energy for both dairy and draught animals. Furthermore, translocated nanoplastics can have an effect on glucose metabolism and cause damage to the liver, which

could reduce the efficiency of metabolic processes during lactation. The exposure also results in gut and rumen microbial dysbiosis, with impacts on bile acid and amino acid metabolism that can impact immune regulation, growth performance and overall herd productivity (Mohamed, 2025) ^[14].

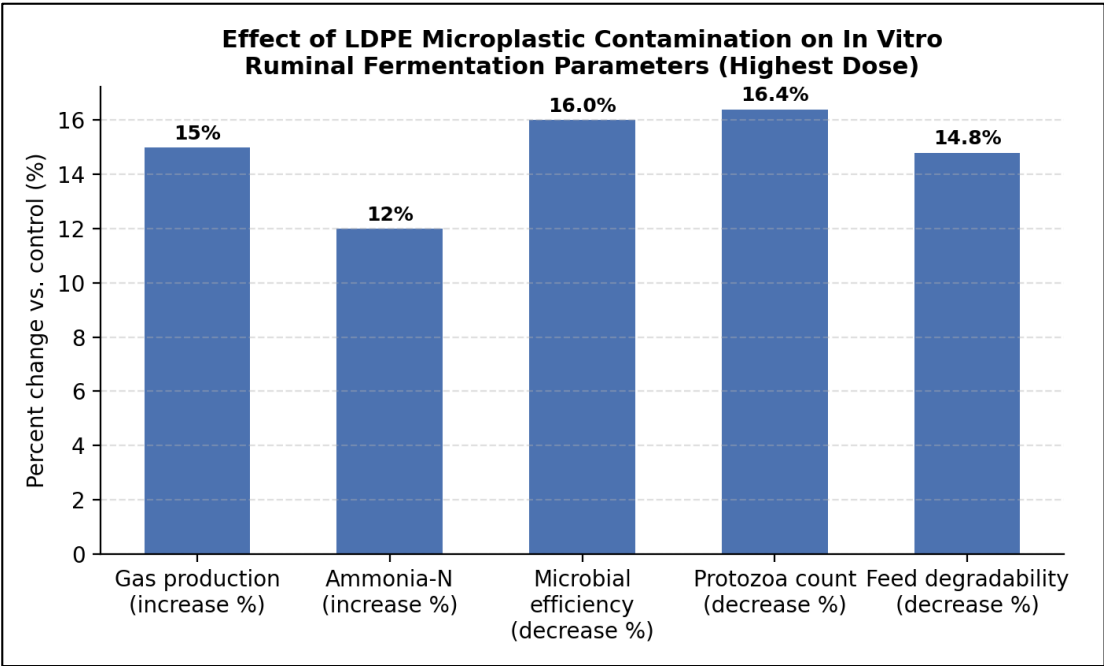


Fig 4: The highest dose of LDPE microplastic contamination significantly altered key *in vitro* ruminal fermentation parameters compared to uncontaminated control rumen fluid.

6. Immune Effects

Mammals respond to the presence of nanoplastic particles with phagocytosis, oxidative burst, and the release of cytokines. Nanoplastic exposure is associated with ROS, NF-κB, and inflammatory signals, cytotoxicity, and genotoxicity. This immune dysfunction can exacerbate malnutrition, heat stress and diseases in the livestock and may affect vaccine efficacy and infection risk. The special properties of nanoplastics may also be able to bind harmful

environmental contaminants and thus increase their immunotoxic effect (Bagavathsingh, 2025) ^[15].

7. Summary of Physiological Effects

Table 1 below summarizes the main endocrine, reproductive, metabolic and immune changes that have been observed after nanoplastic exposure in the mammalian and ruminant evidence base that was included in this study, and are supposed to explain the observed changes.

Table 1: The principal endocrine, reproductive, metabolic, and immune alterations

Physiological System	Key Alteration Reported	Proposed Mechanism	Species/Model
Endocrine	Reduced FSH, LH, testosterone; altered estradiol	ROS-driven NF-κB activation; suppression of StAR, CYP11A1	Mouse/rat models; livestock-relevant Leydig cell studies
Reproductive	Reduced sperm motility/viability, increased abnormality; ovarian follicle loss	Oxidative stress, mitochondrial dysfunction, apoptosis in gonadal tissue	Rodent models; porcine oocyte <i>in vitro</i> maturation
Metabolic	Reduced rumen gas production, altered VFA, increased ammonia-N	Disrupted rumen microbiota and fermentation kinetics	<i>In vitro</i> bovine/ovine rumen fluid (Hohenheim Gas Test)
Immune	Inflammation, cytotoxicity, genotoxicity, immune dysregulation	Particle uptake by immune cells; ROS/pro-inflammatory cytokine cascades	Multiple mammalian <i>in vivo/in vitro</i> systems

8. Species, Breed, and Life-Stage Considerations

Some physiological differences between cattle and buffalo could influence the susceptibility to nanoplastic toxicity. A higher rumen retention time and greater microbial fermentation efficiency in buffalo compared to many cattle breeds could mean that nanoplastics stay longer in the rumen, allowing more time for particles to be broken down and for interaction with microorganisms; however, this could also lead to a higher dose of nanoplastics to which the rumen wall and the microorganisms living there are exposed. Nanoplastics may be ingested more frequently by dairy breeds (Holstein-Friesian and crossbreds) under intensive feeding systems with high use of concentrates and through packaging residue, while peri-urban and riverine

cattle when managed as extensively grazing buffalo or zebu may be exposed to a higher quantity of nanoplastics in the water bodies and floodplain forage (Nahiduzzaman, 2025) ^[2].

Another factor of vulnerability is life stage. Due to the potential of nanoplastics to cross the placental barrier in other mammals, there is concern about endocrine and metabolic programming during pregnancy and the periparturient period in cows and buffaloes. Likewise, bulls before puberty and buffalo bulls in the early stages of testicular development could also be sensitive to nanoplastic-induced disruption of steroidogenic enzyme expression, as shown in juvenile rodent models in which exposure to nanoplastics leads to impaired expression of

steroidogenic enzymes StAR and CYP11A1 in the developing testes (Lackner, 2024) [3]. The metabolic effects described in Section 5, coupled with possible oxidative stress imposed by nanoplastic accumulation and the higher physiological stress that high yielding animals already experience during early lactation, may create a reduced physiological buffer to withstand the added oxidative stress (Mukherjee, 2025) [6].

9. Conclusion

Nanoplastics pollution is a silent and new environmental threat to livestock (buffaloes and cows) health. The evidence from ruminal *in vitro* studies, related livestock animals and mechanistically relevant mammalian models is consistent with a general pattern that exposure to nanoplastics leads to disruption of endocrine signaling, reduced male and female reproductive function, changes in rumen fermentation and systemic metabolism, and to immune dysfunction. Given the importance of cattle and buffalo in global dairy and meat production and the ability of nanoplastics to translocate from gut to blood in production animals, there is a great need for dedicated bovine-and bubaline-specific research to quantify exposure levels, define safe environmental thresholds, and develop veterinary and farm-management interventions to protect animal welfare and food-chain integrity.

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