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Tiny Tech, Big Impact: Nanotechnology in Goat Reproduction

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Abstract

Nanotechnology is emerging as a promising tool for improving reproductive efficiency and productivity in goats through applications in semen cryopreservation, hormone delivery, sperm selection, diagnostics and nutrition. ZnO and Se nanoparticles can protect cryopreserved buck sperm from oxidative damage and improve membrane integrity and heat shock protein expression. Nano-formulated GnRH has also enabled a reduction in hormone dosage without compromising fertility and prolificacy. Nano-minerals such as Zn and Se may further improve milk production, composition, rumen function and udder health. Despite these advances, nanoparticle dose, physicochemical properties and potential toxicity require careful evaluation. Overall, nanotechnology offers promising opportunities for more precise, efficient and sustainable goat production for farmers.

Keywords: Nanotechnology, Zinc oxide, Selenium, GnRH, Goat.

Introduction

Goat production plays an important role in sustainable livestock farming because goats are adaptable animals capable of producing meat, milk and fibre under diverse environmental and management conditions. Reproductive efficiency is a major determinant of productivity, as fertility, kidding rate, prolificacy and efficient dissemination of superior genetics directly influence the performance and profitability of goat production systems. Conventional reproductive technologies such as estrus synchronization, artificial insemination, semen cryopreservation and assisted reproductive techniques have improved genetic management; however, their efficiency can be affected by poor gamete quality, oxidative stress, limited bioavailability of reproductive hormones and difficulties in rapid reproductive assessment.

Nanotechnology refers to materials engineered at an extremely small scale (1–100 nanometers). In goat reproduction, it is helping improve fertility, protect reproductive cells and enhance breeding efficiency. With a diameter below 100 nm, NPs possessing specific physical and chemical properties can be applied in various reproductive biology procedures. With the advancements in nanotechnology, various NPs have been successfully included in semen extenders to improve the quality of cryopreserved semen in bulls, ram, boar and goat bucks. Antioxidant NPs can mitigate the deleterious effects of ROS generated during cryopreservation, further HSPs being molecular chaperones can remodel the sperm surface proteins, thereby shielding against various degrees of cryo-stress.

Nanotechnology has also enhanced nutritional interventions through nano-minerals

such as nano-selenium and nano-zinc, which offer improved bioavailability and more efficient utilization compared with conventional mineral supplements. Furthermore, the integration of nanotechnology in reproductive diagnostics has introduced highly sensitive tools such as nano-biosensors and quantum dots, which enable real-time monitoring of gamete quality and function (Ajayi et al., 2026).

Nanotechnology in Goat Reproduction and Fertility Enhancement

Nanotechnology has emerged as a promising tool in improving reproductive efficiency in goats, particularly through the application of nanoparticles such as nano-selenium (Se) and zinc oxide (ZnO), which function as potent antioxidants. These nanoparticles mitigate oxidative stress by scavenging reactive oxygen species (ROS), a major cause of sperm lipid peroxidation, DNA damage and reduced motility. By stabilizing the sperm plasma membrane and preserving mitochondrial function, nano-supplementation has been shown to significantly enhance sperm motility, membrane integrity and post-thaw viability during cryopreservation processes. The inclusion of nano-Se and ZnO in semen extenders improved sperm kinetics and reduced apoptosis, indicating their protective role at the cellular and subcellular levels.

Nano-formulation of reproductive hormones represents a promising approach for improving the efficiency and precision of reproductive management in goats. Hashem et al. developed a gonadorelin (GnRH) nanoformulation by conjugating the hormone with chitosan–sodium tripolyphosphate (TPP) nanoparticles using an ionic gelation method. The resulting nanoparticles had a mean size of 93.91 nm and exhibited 91.2% GnRH entrapment efficiency. In synchronized Zaraiebi goats, administration of nano-formulated GnRH (12.5 µg) at estrus produced reproductive responses comparable to conventional GnRH administered at 50 µg. Both treatments increased the number of corpora lutea, serum progesterone concentrations, twinning rate, embryo number and prolificacy, while reducing pregnancy losses compared with untreated controls. Importantly, the nanoformulation enabled a 75% reduction in the conventional gonadorelin dose without compromising fertility or prolificacy, demonstrating the potential of nanoparticle-based hormone delivery to improve hormone bioavailability and reduce drug requirements in goat reproductive management (Hashem et al., 2020).

Nanoparticles have also shown considerable potential for protecting buck spermatozoa against oxidative damage during cryopreservation. Abedin et al. investigated zinc oxide (ZnO) and selenium (Se) nanoparticles incorporated into a Tris-citric acid-fructose-egg yolk extender for cryopreservation of goat semen. Supplementation with ZnO nanoparticles at 0.1 mg/mL and Se nanoparticles at 1 µg/mL significantly improved the proportion of spermatozoa possessing intact plasma and acrosomal membranes compared with the frozen control. Transmission electron microscopy further demonstrated that neither ZnO nor Se nanoparticles were internalized into the sperm structure, although occasional interactions with the sperm membrane were observed. Importantly, both nanoparticles increased the expression of heat shock protein (HSP)70 and HSP90, which showed a strong positive association with sperm motility. ZnO nanoparticles were more effective than Se nanoparticles in alleviating lipid peroxidation and preserving sperm quality, suggesting that their antioxidant and cellular stress-protective properties may help maintain sperm ultrastructure and functionality during cryopreservation (Abedin et al. 2023).

Beyond reproductive applications, nanotechnology has considerable potential to improve the productive performance and metabolic health of dairy goats. Nutritional strategies have also benefited from nanotechnology through the use of nano-

minerals like nano-selenium and nano-zinc, which exhibit higher bioavailability and absorption efficiency compared to their conventional counterparts. These nano-supplements play a critical role in boosting antioxidant defense systems, modulating immune responses and supporting endocrine functions associated with reproduction. Zinc oxide nanoparticles (ZnONPs) have received particular attention because of their improved bioavailability compared with conventional zinc sources. In Guanzhong dairy goats, dietary supplementation with ZnONPs at 30 mg/kg dry matter increased milk yield and milk fat content and positively modulated the rumen microbiota, including an increased abundance of beneficial bacteria such as Prevotella, which may contribute to improved nutrient utilization and energy metabolism (Xie et al., 2024). In Barbari goats, dietary nano-zinc supplementation at 10 and 20 ppm did not significantly modify milk composition but reduced somatic cell count, indicating a potential beneficial effect on udder health (Shafi et al., 2020). Similarly, supplementation with ZnONPs at 15 mg/day in Baladi goats significantly increased milk yield and upregulated genes associated with mammary development and milk synthesis, including POU1F1, IGF-1, PPARγ, CSN2, and FASN, suggesting that nano-zinc may influence lactation through molecular regulation of mammary activity (Mansour et al., 2025). Selenium nanoparticles (SeNPs) have also shown potential in supporting lactation, particularly under heat-stress conditions. In dairy goats, SeNP supplementation increased milk yield, milk fat, and lactose content, with these responses associated with modulation of rumen microbiota and enhancement of antioxidant capacity through glutathione-related metabolism (Ying et al., 2025). Collectively, these findings indicate that nano-minerals, particularly Zn and Se, may improve dairy goat productivity through coordinated effects on rumen microbial activity, nutrient utilization, antioxidant defense, mammary function, and udder health.

Nanotechnology also offers potential for selective sperm purification using magnetic nanoparticles, advanced sperm imaging using quantum dots, and sensitive reproductive biosensors (Ajayi et al., 2026), although these applications require further goat-specific validation.

Conclusion

Nanotechnology represents an emerging frontier in goat reproduction and production, offering promising applications in sperm protection, hormone delivery, sperm selection, reproductive diagnostics and nutritional enhancement. In goats, ZnO and Se nanoparticles have demonstrated potential to improve cryopreserved buck semen quality by preserving plasma and acrosomal membrane integrity and enhancing heat shock protein expression, while nano-formulated GnRH has enabled a 75% reduction in gonadorelin dosage without compromising reproductive performance and prolificacy. Nano-mineral supplementation with Zn and Se may further improve milk yield, milk composition, rumen microbial activity, mammary gene expression and udder health in dairy goats. Collectively, these advancements can benefit not only animals but also farmers by improving fertility, facilitating better genetic dissemination, reducing repeated breeding attempts and lowering production costs. The precision of nano-based interventions may also promote more efficient resource utilization and contribute to sustainable livestock production. Nevertheless, nanoparticle dose, physicochemical properties, toxicity, environmental safety and long-term reproductive effects require careful evaluation. With appropriate validation and standardization, nanotechnology has the potential to integrate molecular-level precision with practical on-farm applications, supporting more efficient, economical and sustainable goat production systems.

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