Animal Waste Derived Nanomaterials: A New Paradigm for Biomedical and Environmental Sustainability

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Abstract
The increasing generation of animal waste from livestock, poultry, and aquaculture has emerged as a major environmental concern, while simultaneously presenting an untapped source of valuable biomolecules for sustainable technological applications. Recent advances in green nanotechnology have demonstrated that animal waste, including urine, manure, eggshells, feathers, fish waste, and other agro-industrial by-products, can serve as cost-effective and renewable precursors for the eco-friendly synthesis of diverse nanomaterials. Rich in proteins, amino acids, polysaccharides, minerals, enzymes, and other reducing and stabilizing compounds, these waste streams enable the fabrication of metal, metal oxide, carbon-based, and biopolymeric nanoparticles without the need for hazardous chemicals. The resulting nanomaterials have shown promising biological activities, including antimicrobial, antioxidant, anticancer, anti-inflammatory, wound healing, and drug delivery capabilities, alongside significant environmental applications such as wastewater treatment, pollutant degradation, heavy metal removal, biosensing, and soil remediation. This review provides a comprehensive overview of the emerging role of animal waste-derived nanomaterials, highlighting their synthesis strategies, physicochemical characteristics, and functional properties.

Keywords: waste valorization; nanomaterials; animal waste; sustainable development

1. Introduction

2. Animal waste types and physicochemical properties

The term animal waste refers to manures (liquid and solid forms), hairs, feathers, and other debris produced during the handling or processing of eggs, meat, wool, leather,pearls, milk, and other products. The surge in demand for these goods, driven by the increasing population and evolving lifestyles in developing nations, has resulted in a substantial rise in animal waste production in recent years. Animal waste can be broadly classified into three major groups, including poultry waste, livestock waste, and aquaculture waste.

2.1. Poultry waste

Poultry industry has played a crucial role in ensuring a sufficient food supply for humans, meeting more than one-third of the global demand for meat and eggs. In 2021, the global consumption of poultry meat was 121.59 million tons, and is expected to increase by 181 million tons by 2050. Similarly, global poultry egg consumption has also increased from 61.7 million tons to 76.8 million tons between 2008 and 2018().Poultry practices have been estimated to produce millions of tones waste in the form of manure, feathers, hatchery waste, and slaughtering waste across the world. Manure, which is primarily made up of spilled feed and other bedding ingredients, is the most prevalent form of waste generated by poultry industry. This type of waste contains considerable amount of elemental and non-elemental components such as nitrogen, phosphorus, potassium, carbon and other organic matters. Feathers are another major form of poultry waste, as each chicken produces approximately 5-10% of its body weight in feathers. The primary component of chicken feathers is keratin, a fibrous protein that is resistant to solvents and constitutes around 80% to 90% of the dried feather weight (). The poultry hatchery waste consisted of plenty of solid and semi-solid waste in bird hatching practices, including dead birds, egg shells, dead embryos, and decaying tissue. This waste contains substantial amount of calcium, phosphorus, proteins, and other organic matters.

There is also a substantial amount of waste generated in the process of poultry slaughtering. When a chicken bird is slaughtered, approximately 60-70% of its biomass is converted into meat, while the remaining portion, including offal, visceral organs, blood, and bones, is discarded as waste. These wastes contain both organic and inorganic matter. For example, offal is estimated to be composed of 54% lipids, 32% proteins, 5.3% total nitrogen, and 0.6- 0.9% methane. The visceral trimmings and bones are also composed of proteins, lipids, phosphorous and other organic substances.

2.2. Livestock waste:

Livestock husbandry is a crucial contributor to food and nutrient security in many developing countries across Asia, Africa, Europe, and Latin America. It has been a significant source of income and employment in such nations through the production and trade of various livestock-derived products, such as milk, meat, leather, and horn, at both the national and international levels. In recent decades, the increasing demand for these products, driven by the growing population and changing lifestyles, has led to a substantial rise in global livestock waste generation. Livestock derived waste can be categorized into two primary groups: manure and slaughtering waste. Livestock manure mainly comprises of dung or poof, urine, feed residue, and discarded water. Elderly cattle animal typically produce 30-40 kg of dung and 10-12 liter of urine daily. Mature horses generate 14 kg of dung, whereas mature pigs produce 4 kg of dung. On average, sheep and goats produce 2 kg of dung and 5-10 liter of urine per day. Livestock dung contains ash, cellulose, hemicelluloses, several essential and trace elements such as carbon, calcium, magnesium, manganese, nitrogen, sulfer, boron, and zinc. Livestock urine also contains different types of organic and inorganic substances including minerals, salts, hormones, and amino acids. For instance, cow urine contains 95% water, 2.5% urea, minerals, 24 types of salts, hormones, amino acids, and 2.5% enzymes(). Livestock slaughtering waste are the most abundant waste of commercial municipal solid waste. In 2021, the total world meat production is 354.82 million tons and is mainly contributed by pigs (120.37 million tons), beef and buffalo (76.77 million tons), sheep and goats (16.36 million tons), horse(0.7 million tons), and camel (0.6 million tons). Generally, the bovine slaughterhouse generates solid waste of 27.5% of the animal weight whereas for goat and sheep slaughterhouse, the waste generation is equivalent to 17% of animal weight. Similarly, during pig slaughtering, an average waste generation is 2.3 kg/head that is equivalent to 4% of animal weight.

3. Synthesis and applications of animal waste derived nanomaterials

3.1. Biomedical application

Type of animal waste	Used waste	Synthesised nanomaterials	Size and shape of NMs	Application	Reference
Livestock waste	Cow urine	Silver oxide (Ag_2O) NPs	-	Anticancer	Venkatesh and Appikonda, 2026
	Cow urine	Bismuth vanadate ($BiVO_4$) NPs	Size 38.1 nm; shape spherical	Antioxidant and anticancer properties	Ghotekar et al., 2025
	Cow urine	zinc oxide, iron oxide and zinc-iron nanoparticle composite	420.7, 200.7, and 247.7 ± 27.9 nm, irregular shape	anticancer and anti-inflammatory properties	Hiremath et al., 2025
	Cow urine distillate	copper (Cu)NPs	232.76 nm;	Antimicrobial and antioxidant properties	Angle et al., 2025
	Cow urine	Carbon dots	-	Cancer diagnosis and targeted cancer therapy	Chellachamy Anbalagan et al., 2024
	Cow urine	silver oxide NPs	18 nm; spherical	Anti-oxidant properties	Allaka et al., 2023
	Cow dung	Silver NPs	39 nm; rounded	Antimicrobial properties	Das et al., 2025
	Cow dung	Nanocellulose	-	Wound dressings, antimicrobial coatings, and tissue engineering	Yadav et al., 2025
	Cow dung	Mg doped carbon dots (M-CDs)	-	biological probe for cancer cells imaging	Koparde et al., 2024
	Cow dung	hydroxyapatite (HAp) NPs	-	Biomedical applications	Razak and Gamagedara, 2025

	Donkey dung	Silver NPs	36 nm	Antimicrobial, anticancer and DNA cleavage	Mousavi-Khattat et al., 2022
	Cow dung	copper (Cu)NPs	51.8 nm	Antibacterial properties	Yao et al., 2021
	Sheep blood serum	Silver(Ag) NPs	Spherical, 32.49 nm	Antibacterial activity	Kakakhel et al., 2021
	Goat fur	Silver NPs	11.67-31.47 nm;	antioxidant, anticoagulant, thrombolytic agents	Akintayo et al., 2020
	Goat and sheep fecal matter	Silver NPs		Antibacterial properties	Chikkanna and Neelagund, 2018
	Sheep milk	Platinum(Pt) NPs	9 nm; Spherical	drug discovery and gene transfer technologies	Gholami-Shabani et al., 2016
Poultry waste	Chicken eggshells	Calcium NPs	-	pro-angiogenic properties	Nagchowdhury et al., 2025
	Chicken eggshells	calcium oxide (CaO) NPs	5-30nm; spherical	Antimicrobial properties	Hemmami et al., 2024
	Chicken eggshells	hematite (α-Fe2O3) NPs	spherical	Antioxidant, antibacterial and bone implantation	Ayub et al., 2023
	pigeon dropping	silver NPs	135 nm; Spherical	Antimicrobial and anticancer	Awad et al., 2019
Aquaculture waste	Fish waste	Nanosilver	2 to 20 nm, 20–40 nm	Antimicrobial properties	Das et al., 2024
	Biofloc Waste	Silver NPs	22.4 nm	Antimicrobial activity	Gomes et., 2024
	Discarded shells of Carinosquilla multicarinata	Chitosan NPs	248 nm; spherical	delivery of anti-inflammatory drug	Balde et al., 2020
	Crab shells	Apatite NPs	24.4 nm, needle-like nanorods	As biomaterial in bone/teeth implants	Bhattacharjee et al., 2019

Other biowaste	Dead honeybees	silver NPs	79 and 91 nm	antioxidant and antimicrobial properties	Keskin and Keskin, 2026
	Termites Wings	silver NPs, zinc oxide NPs and silver-doped zinc oxide NPs	28.4, 19.6, and 11 nm, respectively	Antioxidant and anticancer properties	Surya et al., 2025
	Gland extract of Mupli beetle	Silver NPs	10 to 20 nm	Antibacterial, antioxidant and anticancer properties	Ajaykumar et al., 2023
	Insect (Mang mao) wings	Silver NPs	Spherical, 40–60 nm	Antioxidant and antimicrobial activity	Jakinala et al., 2021
	Cockroach wings	Silver NPs	Spherical, less than 50 nm	Insecticidal properties	Khatami et al., 2019

3.2. Environmental restoration

Used animal waste	**Synthesised nanomaterials**	**Charterstics of NMs**	**Application**	**Reference**
Cow urine	zinc cobaltite ($ZnCo_2O_4$) NPs	Size 28.27 nm	photocatalyst for wastewater treatment (Rhodamine B dye)	Pagar et al., 2026
Cow urine	CuO nano bundle	15.76 nm; bacillus-like structures	Photodegradation (malachite green dye) and treating refractory pollutants from wastewater	Nandisha, 2023
Cow urine	Silver NPs	90-200 nm; spherical	photo catalytic degradation(Methylene blue and Crystal violet)	Sarvalkar et al., 2021
Cow urine	Graphene nanosheets (GNs)	High conductivity and transparency	Environmental assessment	Chamoli et al., 2020

Cow urine	Silver oxide NPs	Size 20 nm; spherical shape	photo catalytic degradation (methylene blue)and photoluminescence	Vinay et al., 2019
Pig manure	cobalt-loaded biochar (Co-BC)	-	peroxymonosulfate activation and water remediation	Jiang et al., 2026
Cow dung	Mg doped carbon dots (M-CDs)	-	biological probe for environmental pollutant sensing	Koparde et al., 2024
Cow dung	Porous activated carbon	-	modified electrode fabrication and super capacitor	Ramalingam et al., 2020
Goat slaughter waste	Zinc oxide (ZnO) NPs	3-11 nm	Environmental protection	Jha and Prasad, 2016
Chicken eggshells	calcium oxide (CaO) NPs	5-30nm; spherical	adsorbents for heavy metal (Pb, Cr, Cd, Hg) remediation	Hemmami et al., 2024
Chicken egg shell	calcium oxide (CaO) NPs	rod-shaped	photocatalytic degradation(methylene blue) and electrochemical applications	Adaikalam et al., 2024
Chicken egg shell	CaO nanocrystals	irregular surface nanohybrid	photocatalyst for heavy metal removal	Rani et al., 2023

3.3. Other Miscellaneous applications (Green energy, sustainable agriculture)

4. Rules/regulations concerning the safety issues

5. Concluding remarks and future possibilities

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