Waste-Derived Biomaterials: An Emerging Approach for Sustainable Biomedical Applications

Lhingneivah Doungel[1*], Joycy Seiba Khukhodziinai[2]

[1]Assistant Professor, Department of Veterinary Anatomy, M.R College of Veterinary Science & Research Centre (Approved by VCI, Affiliated to LUVAS, Hisar), Jhajjar, Haryana-124103, India.

[2]Assistant Professor, Department of Veterinary Physiology, M.R College of Veterinary Science & Research Centre (Approved by VCI, Affiliated to LUVAS, Hisar), Jhajjar, Haryana-124103, India.

*Correspodance: lhingneivahdoungel@gmail.com

VETERINARY TODAY INTERNATIONAL
ISSN 2583-8288

doi.org/10.5281/VeterinaryToday.22693731

Introduction

The increasing generation of biological, agricultural, food-processing, and animal-derived waste has become an important environmental and economic concern. Conventional disposal of these wastes through landfilling or other methods can contribute to environmental pollution and the loss of potentially valuable biological resources (Jana *et al.* 2022). In recent years, considerable attention has therefore been directed toward the valorization of biological waste into value-added biomaterials for biomedical applications (Moazzam, 2025). Waste-derived biomaterials represent an emerging class of sustainable materials that can combine the advantages of naturally derived biomaterials with the principles of waste reduction and circular bioeconomy (Tarafdar *et al.* 2021).

Biological wastes originating from fruit and vegetable processing, fisheries, meat and poultry industries, livestock production, and agricultural activities contain a wide range of valuable organic and inorganic components (Zamri *et al.* 2021, Cao *et al.* 2025). These include collagen, gelatin, chitin, chitosan, cellulose, pectin, eggshell membrane proteins, calcium carbonate, hydroxyapatite, and other calcium phosphate compounds. Such components can be processed into scaffolds, membranes, hydrogels, wound dressings, drug-delivery systems, and other biomaterials for tissue engineering and regenerative medicine (Bee and Hamid, 2020).

Sources of Waste-Derived Biomaterials

Waste-derived biomaterials can broadly be classified according to their biological origin.

Animal-derived wastes include bones, skin, tendons, cartilage, scales, shells, feathers, eggshells, and other by-products of livestock, poultry, fishery, and slaughterhouse industries (Corridon *et al.* 2025). These materials are rich sources of proteins and minerals that can be recovered and converted into useful biomaterials. Collagen and gelatin can be obtained from skin, tendons, bones, and other connective tissues, whereas chitin and chitosan can be obtained from crustacean shells. Bones, eggshells, and fish scales are particularly important sources of calcium-rich compounds for the production of hydroxyapatite and other calcium phosphates (Abdulrahman *et al*. 2014, Tarafdar *et al.* 2021).

Plant and agricultural wastes represent another important source of biomaterial precursors.

Agricultural residues and food-processing wastes may contain cellulose, hemicellulose, lignin, pectin, starch, proteins, and other bioactive compounds. These materials can be processed into films, fibers, hydrogels, scaffolds, and composite biomaterials. The conversion of such waste into biomedical materials provides an opportunity to reduce environmental burdens while creating economically valuable products (Sah *et al*. 2022, Corridon *et al.* 2025).

Animal Waste as a Source of Biomaterials

Animal-derived waste has considerable potential in biomedical engineering because of its abundance and the presence of naturally occurring biological molecules (Tarafdar *et al.* 2021). Waste generated from cattle, sheep, goats, pigs, poultry, and slaughterhouses can serve as a source of collagen, gelatin, keratin, hydroxyapatite, and other biomaterial precursors (Corridon *et al.* 2025). These materials can be processed through physical, chemical, enzymatic, or thermal methods depending on the desired end product.

Collagen is particularly important because it is a major structural protein of the extracellular matrix. Collagen-based materials can provide a favorable biological environment for cellular adhesion, migration, proliferation, and differentiation. Similarly, gelatin obtained through controlled processing of collagen can be incorporated into hydrogels, films, and three-dimensional scaffolds. These properties make collagen and gelatin-derived materials attractive for tissue engineering, wound healing, and regenerative medicine (Razak *et al.* 2022).

Keratin-containing wastes, particularly feathers and other keratin-rich animal by-products, have also attracted attention as potential sources of biomaterials (Shavandi *et al.* 2017). Keratin possesses functional groups capable of interacting with cells and other biomolecules and may therefore be incorporated into scaffolds and composite materials (Sarma, 2022). However, appropriate extraction, purification, sterilization, and characterization are necessary before animal-derived waste materials can be considered for biomedical applications (Feroz *et al.* 2020).

Waste-Derived Hydroxyapatite

Among waste-derived biomaterials, hydroxyapatite (HAp) has received considerable attention because of its similarity to the inorganic mineral component of natural bone and teeth (Ramesh *et al.* 2026). HAp has excellent biocompatibility and bioactivity and is widely investigated for bone tissue engineering, bone graft substitutes, dental applications, and coating of metallic implants (Yadav *et al.* 2023).

Several biological wastes, including animal bones, eggshells, fish scales, and seafood shells, are rich in calcium and can serve as precursors for the production of HAp and other calcium phosphate materials. Waste-derived HAp can therefore provide an alternative to conventional synthetic sources while simultaneously contributing to waste valorization (Kareem and Eliyer, 2024).

Eggshell is particularly promising because it contains a high proportion of calcium carbonate. Through suitable processing and conversion methods, eggshell-derived calcium can be transformed into hydroxyapatite (Shanti Swarup *et al.* 2025). Studies have demonstrated that eggshell-derived HAp has potential for tissue engineering and regenerative applications. Recent reviews have further highlighted eggshell-derived HAp as a promising biomaterial because of its availability, affordability, biocompatibility, osteoconductivity, and environmental advantages (Ramesh *et al.* 2026).

Applications in Tissue Engineering and Regenerative Medicine

The principal advantage of waste-derived biomaterials is their potential to provide biologically active and structurally appropriate materials for tissue regeneration. Natural polymers such as collagen, gelatin, chitosan, cellulose, and pectin can be processed into scaffolds that provide support for cell attachment and proliferation. These materials can also be modified or combined with inorganic components to improve their mechanical and biological properties (Sah *et al*. 2022).

In tissue engineering, scaffolds are required to provide a suitable three-dimensional environment for cellular activities while gradually degrading as new tissue develops. Waste-derived biomaterials may satisfy several of these requirements because many naturally derived polymers are biodegradable and possess favorable biological characteristics. Waste-derived proteins and polysaccharides have therefore been investigated for applications in wound healing, drug delivery, tissue engineering, and regenerative medicine (Zamri *et al.* 2021).

Hydroxyapatite derived from biological waste is particularly relevant to bone and dental tissue regeneration. Its chemical similarity to the mineral phase of bone makes it suitable for incorporation into scaffolds and composites intended to support bone formation. Waste-derived HAp can also be combined with polymers such as collagen, gelatin, chitosan, or other biodegradable materials to produce composite scaffolds with improved biological and mechanical characteristics (Yadav *et al.* 2023, Ramesh *et al.* 2026).

Advantages of Waste-Derived Biomaterials

The conversion of biological waste into biomaterials provides several potential advantages. First, it can reduce the amount of waste requiring disposal and thereby contribute to environmental protection. Second, waste materials are often inexpensive and readily available, which may reduce the cost of raw materials for biomaterial production. Third, biological wastes can contain naturally occurring molecules and minerals with desirable biological properties (Sah *et al*. 2022).

Waste-derived biomaterials can also contribute to a circular bioeconomy, in which waste streams are converted into useful products rather than being treated solely as materials requiring disposal. This approach can simultaneously address environmental concerns and create value from agricultural, food-processing, and animal-industry by-products (Moazzam 2025).

Challenges and Limitations

Despite their considerable potential, several challenges must be addressed before waste-derived biomaterials can be widely adopted for biomedical applications. The composition of biological waste can vary according to species, age, geographical origin, processing conditions, and storage methods. Such variation can affect the chemical, physical, mechanical, and biological properties of the final biomaterial (Zamri *et al.* 2021).

Another major concern is biosafety. Animal-derived materials may carry microorganisms, endotoxins, proteins, or other biological contaminants. Therefore, appropriate purification, sterilization, and characterization procedures are essential. Standardized protocols for processing waste materials and producing biomaterials on a larger scale are also required. Reviews of animal-derived waste have identified the lack of standardized large-scale production protocols and organized waste-to-biomaterial supply chains as important barriers to commercialization (Moazzam, 2025).

Furthermore, the long-term biocompatibility, degradation behavior, mechanical strength, immunological response, and clinical performance of many waste-derived biomaterials require further investigation (Kumar *et al.* 2015). Although promising laboratory and preclinical findings are available, more standardized studies and well-designed clinical investigations are needed before these materials can replace established commercial biomaterials (Jana *et al.* 2022).

Future Perspectives

Future research should focus on developing standardized and reproducible methods for the collection, processing, purification, and characterization of biological wastes. Advanced technologies such as nanotechnology, electrospinning, three-dimensional printing, and controlled chemical modification may further improve the performance of waste-derived biomaterials (Kumar *et al.* 2015).

The development of composite materials combining waste-derived organic and inorganic components is another promising approach. For example, collagen or gelatin derived from animal waste can potentially be combined with waste-derived hydroxyapatite to produce biomimetic scaffolds for bone and soft-tissue regeneration (Bee and Hamid, 2020). Such approaches could provide materials with complementary biological, structural, and mechanical properties (Jana *et al.* 2022).

Recent research on eggshell-derived HAp demonstrates the continuing development of waste-to-biomaterial approaches (Yadav *et al.* 2023). Current studies are examining different synthesis methods and optimizing the physicochemical properties of eggshell-derived HAp for biomedical applications (Kareem and Eliyer, 2024).

Conclusion

Waste-derived biomaterials represent a promising and sustainable approach to the development of materials for biomedical and tissue-engineering applications. Biological wastes from animal, agricultural, food-processing, and fisheries industries contain valuable proteins, polysaccharides, and mineral components that can be converted into functional biomaterials. Collagen, gelatin, chitosan, keratin, cellulose, pectin, and hydroxyapatite are among the most important examples.

The conversion of waste into biomaterials provides a dual benefit by reducing environmental waste while generating value-added materials for healthcare applications. In particular, animal bones, eggshells, and fish scales provide promising sources of hydroxyapatite for bone and dental tissue engineering. Nevertheless, issues related to standardization, biosafety, reproducibility, scalability, and long-term clinical performance must be addressed. With continued research and appropriate regulatory development, waste-derived biomaterials have considerable potential to contribute to sustainable tissue engineering, regenerative medicine, and the emerging circular bioeconomy.

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