MIKAILALSYS
Journal of Multidisciplinary Sciences

e-ISSN : 2987-2286
p-ISSN : 2987-3924

Index : Dimensions, Scilit, Crossref, Garuda, Semantic, Lens,Google Scholar,Base, etc

https://doi.org/10.58578/mikailalsys.v4i1.8630

Applications of Microbial Proteases: A Review

Samuel Adedayo Fasiku, Femi Johnson Afolabi, Christiana Ify Odeyale
Ajayi Crowther University, Oyo-Town, Nigeria
samfash4@yahoo.com

Article Info:

Submitted:	Revised:	Accepted:	Published:
Dec 31, 2025	Feb 5, 2026	Feb 28, 2026	Mar 8, 2026

Abstract

Microbial proteases have attracted increasing attention as eco-friendly biocatalysts because of their broad functional versatility and advantages over proteases derived from plants and animals. This review examines the major sources, classification, production methods, and sectoral applications of microbial proteases. Produced by bacteria, actinomycetes, and fungi, microbial proteases are classified according to optimum pH range, catalytic mechanism, and site of action, and are commonly generated through submerged and solid-state fermentation. The review shows that these enzymes have diverse industrial applications in detergent, leather and tanning, food and dairy, brewing and beverage processing, and textile production. In medical and pharmaceutical contexts, microbial proteases are applied in wound debridement and healing, antimicrobial and antibiofilm activities, drug development, diagnostics, and therapeutic interventions. In agriculture, they support animal feed supplementation by improving protein digestion and function as biological control agents by disrupting pathogen attachment, penetration, and colonization of plant tissues. In the environmental sector, their applications include waste management, bioremediation, and the recycling of keratinous and other protein-rich wastes. Overall, this review underscores the wide-ranging utility of microbial proteases across industrial, medical, agricultural, and environmental sectors, highlighting their potential as sustainable biological agents for diverse biotechnological applications.

Keywords: Biocatalysts; Fermentation; Microbial Proteases; Sustainable Biotechnology; Waste Bioremediation

Introduction

Enzymes are a type of catalyst that play an important part in sustaining life. They speed up the rate of biochemical reactions without getting used up in the process, and most of them are proteinaceous (Oke *et al*., 2023). The specificity of enzymes in action and efficiency is well recognised. They achieve their action efficiently and in an optimum manner at specific physicochemical conditions like temperature, pH, and substrate concentration (Fasiku *et al*., 2023). These catalysts are much more effective than inorganic ones. As much as industrial processes are dependent on enzymes, biological systems are also dependent on enzymes

Enzymes come in different classes. Proteases are one of the classes of enzymes that have been extensively studied (Fasiku *et al*., 2020; Moonnee *et al*., 2021; Solanki *et al*., 2021; Ghoreishi *et al*., 2022; Kotb *et al*., 2023; Ojo-Omoniyi *et al*., 2024; Eskilson *et al*., 2025; Khatami *et al*., 2026). The enzymes that catalyse the breaking of the peptide bond between amino acids in a protein molecule are called proteases. Proteases react with various sites of polypeptide chains. Some of these may act on the terminal ends of the chain; others can act within the internal peptide bonds. Enzymatic activity facilitates the breakdown, modification, or activation of proteins that occur in industrial and biological systems (Reddy *et al*., 2022). Proteases are also called proteinases and peptidases. The various physiological processes that involve different proteases include digestion, protein turnover, cell signalling, immune responses, and apoptosis.

Plants, animals, and microorganisms produce proteases. Proteases have gained much attention due to their properties, that they are secreted extracellularly, being produced with ease, being highly stable, and having broad substrate specificity. An increasing interest in proteases as green alternatives to chemical catalysts is accelerating due to advances in enzyme technology and industrial biotechnology. Industries are searching for sustainable bioprocesses at an affordable level (Adetunji *et al*., 2023). Microbial proteases have a great importance in the areas of detergents, food industry, leather tanning, pharmaceuticals, agriculture, and waste treatment. As a result of their ability to replace chemical catalysts, their use has contributed to cleaner production with less impact on the environment. A group of enzymes that are the alkaline proteases from *Bacillus* species are widely used to formulate detergents due to their effectiveness (Fasiku *et al*., 2020).

With the development of molecular biology and other advanced techniques, the usage of microbial proteases has increased. Genetic alterations have enhanced the substrate specificity and thermostability of proteases. As a result of these developments, there have been improvements in performance and lower production costs of protease, qualifying them for industrial use (Reddy *et al*., 2022). Microbial proteases are important in industrial biotechnology. Their biochemical diversity, production efficiency, and wide range of potential applications for industrial, medical, agricultural, and environmental problems make them valuable. The demand for enzymes is increasing worldwide. The growing demand for protein-degrading enzymes has made proteases the biggest commercial enzyme (Song *et al*., 2023). Due to their greater prominence, a lot of research is being done on their sources, production, and other possible uses.

Microbial Proteases

Microbial proteases are detected when clear halos are formed around the producing microbes on agar plates containing protein substrates. Some of the protein substrates used for the detection of protease are skimmed milk agar (Fasiku *et al*., 2020), elastin agar (Fortuna *et al*., 2023), fibrin agar (Umay *et al*, 2023; Lutpiatina *et al*., 2025), keratin agar (Moonnee *et al*., 2021; Song *et al*., 2023), gelatin agar (Jayasheree and Pan, 2025), bovine serum albumin agar (Elshazly *et al*., 2022) and casein agar (Song *et al*., 2023; Jayasheree and Pan, 2025). Microbial proteases are proteinaceous enzymes which are produced by microorganisms like bacteria, fungi, and actinomycetes. They can either be intracellular or extracellular. Microbial proteases, which are extracellular, are of more significance because they can easily be harvested from the media of fermentation, which reduces the cost of downstream processing (Solanki *et al*., 2021). Microbial proteases play important roles in natural ecosystems. They take part in breaking down and recycling organic nitrogen. They contribute to the cycling of nutrients by breaking down complex proteins into forms which can easily be absorbed. This supports the growth of microorganisms and maintains ecological balance. Their importance to the ecosystem is attributed to their functional adaptability (Song *et al.*, 2023).

Extremophilic microorganisms are microorganisms that can thrive under extreme conditions like high temperature, extreme pH, and high salinity. Extremozymes proteases are proteases produced by extremophilic microbes; they possess good stability and are very functional under conditions that would naturally denature other enzymes (Yao *et al.*, 2023). Thermophilic proteases refer to proteases that remain active even at very high temperatures. These make them valuable for industrial processes which require high thermal stability. Proteases which retain their activity in high salt concentrations are referred to as halophilic proteases. They are used in the production of detergents and in saline waste treatment. The use of extremophilic proteases reduces enzyme loss and enhances overall efficiency, thereby reducing the cost of operation (Yang *et al.*, 2023; Ashaolu *et al.*, 2024; Salas-Bruggink *et al.*, 2024).

Sources of Microbial Proteases

Microbial proteases are obtained from a wide variety of microorganisms which occur in terrestrial, aquatic, and extreme environments. These organisms have evolved to develop proteolytic systems, which help them to make use of proteinaceous materials as a source of carbon and nitrogen effectively and efficiently. Microorganisms have an ecological advantage due to being able to secrete proteases extracellularly. As a result, they are exploited in industrial enzyme production (Song *et al.*, 2023). Microbial proteases have more advantages than plant and animal proteases. High yield, economic cultivation, consistent enzyme quality, and simple scaling up are some of the advantages of microbial proteases over other sources. Furthermore, microbial systems can be genetically manipulated, and the fermentation can be controlled easily. This helps in developing enzymes with better tolerance to pH and specificity towards substrate (Reddy *et al.*, 2022). Microorganisms are superior sources of proteases for industrial and commercial applications due to these features.

Bacterial Proteases

Bacteria are the most commonly used microbes in the production of proteases because they have a short generation time and can grow on rather inexpensive substrates (Fasiku *et al.*, 2023). They can also secrete large amounts of extracellular enzymes. *Bacillus* species are the most important microbes used for industrial protease production due to their high enzyme yield and their non-pathogenicity (Khan *et al*., 2023). Different *Bacillus* species proteases generally possess alkaline characteristics and are stable at extreme temperatures and pH environments. Their properties make them suitable for the manufacture of detergents, leather, and textiles, where manufacturing conditions are quite harsh, and the enzymes need to remain active without being denatured. Besides this, bacterial proteases show a wide variety of substrate specificity and can degrade various types of proteinous materials effectively (Song *et al*., 2023). As a result of certain advancements in recombinant DNA techniques, bacterial proteases have become significant in some applications. The cloning and expression of proteolytic genes can be done in suitable host systems, which enhances yield and catalytic properties. Advancements such as this are lowering the cost of production significantly while improving the functional properties of microbial proteases (Reddy *et al*. 2022).

Fungal Proteases

Another major source of microbial proteases is fungi, especially for processes which require enzymes which are active at acidic or neutral pH. Filamentous fungi like *Aspergillus, Penicillium, Rhizopus*, and *Mucor* are used in industrial fermentation systems because they produce high secretions and are adaptable to solid-state fermentation (Gandia & Garrigues, 2024; Khatami *et al*., 2026). Proteases, which are derived from fungi, are of high value in the production of food and beverages where flavour development, modification of texture and product clarification are dependent on controlled protein hydrolysis. For example, *Aspergillus* species are commonly used in manufacturing cheese and also in the process of beverage clarification, as they produce acidic proteases. Their substrates are highly specific and thereby reduce the risk of excessive protein degradation, which could result in low quality (Ojo-Omoniyi *et al*., 2024). Other than their functional advantage, fungal proteases can also be produced using agro-industrial residues under solid-state fermentation conditions. This reduces the cost of production and also contributes to environmental sustainability (Fasiku *et al*., 2023; Ravi *et al*., 2025).

Actinomycetes proteases

Species of actinomycetes belonging to the genus *Streptomyces* are known for their ability to produce proteases, which happen to have special biochemical properties. The characteristics of these organisms are intermediate between bacteria and fungi. They are known for synthesising enzymes which have high stability and are catalytically efficient. Proteases, which are obtained from actinomycetes, are usually neutral or alkaline in nature and show strong proteolytic activity against complex substrates. This makes them ideal for usage in pharmaceutical applications, protein hydrolysate production, and biotechnological research (Song *et al*., 2023).

Classification of Microbial Proteases

Microbial proteases can be classified on various bases. Enzymes can be divided based on their catalytic mechanisms and the conditions in which they work most efficiently. This classification system provides a way to understand how enzymes work, as well as the use of certain proteases for specific industrial uses (Aruna *et al*., 2023). Proteases can be classified as exopeptidases and endopeptidases depending on their site of action. Exopeptidases hydrolyse peptide bonds of amino acids from the N- and C-terminus ends of polypeptides (Song *et al*., 2023). Endopeptidases cleave the peptide bonds in the internal region of the protein chains.

Classification based on Catalytic Mechanism

Serine Proteases: Serine proteinases are the largest and most commercially important microbial proteases. A serine residue in their active site plays a crucial role in the breaking down of peptide bonds. Under alkaline conditions, they are stable, and they have broad substrate specificity. Due to this, they are perfect for detergents and other industrial cleaning formulations (Song *et al*., 2023).

Cysteine Proteases: There is a presence of cysteine residue in the catalytic mechanism of cysteine proteases, which helps in regulatory and physiological processes. Due to their capacity to break down proteins, proteolytic enzymes have garnered attention in pharmaceutical and biomedical applications (Borges *et al*., 2024; Putri, 2024; Jamal *et al*., 2025).

Aspartic Proteases: These proteases are characterised by optimum activity under acidic conditions. They are mostly produced by fungi. The food processing industries, which include cheese making and clarification of beverages, utilise this type of protease. In biological processes where selective degradation of proteins occurs, aspartic proteases are used (Kumar *et al*., 2024).

Metalloproteases: These are proteases which require metal ions like zinc or calcium for their catalytic activity. They are thermally stable and are used in protein hydrolysis, peptide synthesis, and treatment of waste (Reddy *et al*., 2022).

Classification Based on Optimum pH

Microbial proteases can also be categorised based on their pH preference. They can be categorised into acidic, neutral and alkaline proteases. Acidic proteases are proteases which function most efficiently at low pH. They are used in the food and beverage industries. Neutral proteases operate close to physiological pH and are used mainly in pharmaceutical and diagnostic applications. Alkaline proteases show optimal activity at high pH values and are the most used in the industrial sector, such as in the production of detergents and leather processing (Yao *et al*., 2023).

Production of microbial proteases

Microbial proteases are produced through submerged or solid-state fermentations. Submerged fermentation involves the cultivation of microorganisms in liquid nutrient media with controlled parameters such as pH, temperature, aeration and agitation. Submerged fermentation has a wide range of applications in the production of bacterial proteases. This is because it is easy to monitor. However, it is associated with additional input of energy, which often results in a higher cost of production (Reddy *et al*., 2022). Solid-state fermentation (SSF) uses solid substrates, which have very little free water. Filamentous fungi find it very suitable to use solid substrates. Solid-state fermentation is beneficial because of its higher concentration of enzymes, lower energy requirements, and ability to efficiently use agro-industrial residues, which has a great promise (Ojo-Omoniyi *et al*., 2024).

Industrial Applications of Microbial Proteases

The global industrial enzyme market primarily relies on microbial proteases as a foundation. This is due to their extraordinary and cost-effective catalysts, versatility, and economic viability. Many industries are using them increasingly to substitute the often-toxic chemical treatment with biological processes, which are much more environmentally friendly. Microbial proteases, in contrast to chemical catalysts, operate under operationally mild conditions. This minimises energy use and minimises the production of toxic byproducts. The international sustainability goals, as well as regulatory pressures aimed at reducing industrial pollution, have helped the transition to microbial proteases (Adetunji *et al*., 2023; Song *et al*., 2023).

Also, microbial proteases are structurally and functionally diverse. This enables their application in industries where processing requirements are highly variable. Industries are able to select enzymes which are tailored to specific pH and temperature conditions as a result of the availability of alkaline, neutral and acidic proteases. Enzyme stability, catalytic efficiency, and resistance to inhibitors have been enhanced by advances in fermentation technology and protein engineering. This has resulted in an expansion in their industrial relevance (Reddy *et al*., 2022). As a result of this, microbial proteases are now indispensable in the formulation of detergents, processing of leather, production of food, brewing, and manufacturing of textiles.

Application in the Detergent Industry

The detergent industry is the single largest consumer of microbial proteases. This industry accounts for a substantial amount of the demand for proteases globally. Alkaline proteases that are primarily obtained from *Bacillus* species are used in the production of laundry and dishwashing detergents. This is because of their ability to hydrolyse proteinaceous stains like blood, food, milk, egg, and other food residues (Kotb *et al*., 2023). These stains are usually insoluble in water, and hence they are difficult to remove using only surfactants, necessitating the intervention of enzymes (Song *et al*., 2023).

Microbial proteases can enhance the performance of detergents by breaking down molecules of protein into smaller, water-soluble peptides and also amino acids, which can then be easily washed away. They are suitable for the formulation of modern detergents because they are effective at high pH and elevated temperatures. The use of microbial proteases enables washing to be effectively carried out at a low temperature. This conserves energy and also reduces damage done to the fabric. Continuous optimisation of enzymes has resulted in the development of proteases which are more resistant to bleaching agents, oxidants, and also surfactants, which significantly enhances their shelf life and operational efficiency (Yao *et al*., 2023).

Application in the Leather and Tanning Industry

Microbial proteases have greatly improved traditional methods of processing hides in the tanning and leather industry. In the past, harmful chemicals such as lime and sodium sulfide were used. They are, however, known to produce highly toxic effluents, which can cause occupational health problems and also cause substantial environmental pollution. Protease-based processing methods provide a more sustainable option. During the dehairing and bating stages, non-collagenous proteins are broken down without damaging the collagen matrix, which is an essential leather quality (Khan *et al*., 2023). Proteolytic enzymes allow cleaner dehairing by loosening up hair roots and getting rid of epidermal proteins. This results in a smoother hide with improved softness, elasticity, and grain. The leather's soft, supple texture and consistent quality are achieved through enzymatic batting. Residual proteins are eliminated, and chemical load is reduced by the usage of microbial proteases. Microbial proteases also lower the toxicity of wastewater, thereby improving compliance with environmental regulations. Leather processing involving the use of proteases is increasingly recognised as an important aspect of eco-friendly operations (Zhou *et al*., 2018).

Application in the Food and Dairy Industry

Microbial proteases are significant for the processing of food and dairy, which includes cheese. They accomplish this by applying controlled hydrolysis to the protein. When food is fermented, its flavour, texture, digestibility, and nutritional value improve as well. Microbial proteases can be used as substitutes for rennet, which is derived from animals, in cheesemaking. They help in coagulating proteins in milk to form curds. The replacement of alternative proteases with microbial proteases is geared towards overcoming and eliminating the ethical, religious, and supply constraints associated with the use of animals (Adetunji *et a*l., 2023; Song *et al*., 2023).

Microbial proteases are not only used to manufacture cheese; they are also widely used for the tenderization of meat, baking, and the production of protein hydrolysates. The tenderness of meat can be improved by proteolytic treatment; this is done by breaking down muscle proteins and connective tissues. Microbial proteases can produce easily digestible peptides with better bioactivity during the hydrolysis of proteins. This makes them very valuable in infant nutrition, the production of sports supplements and clinical diet. In addition to this, microbial proteases can also be used in beverage industries as they prevent the formation of haze by breaking down proteins which form haze. This improves clarity, stability, and also consumer acceptability (Ojo-Omoniyi *et al*., 2024).

Application in the Brewing and Beverages Processing

Microbial proteolytic enzymes significantly contribute to the brewing and beverage manufacturing processes. This ultimately leads to a higher quality of the products and enhanced efficiency of the process. Protein-polyphenol complexes contribute greatly to the haze formation in beer and fruit beverages. This results in less clarity and a shorter shelf life. Microbial proteases can, however, hydrolyse these proteins into smaller fragments, thereby preventing haze formation. The impact of this is clearer and more stable products (Kumar *et al.*, 2024). Proteases can also improve the efficiency of the fermentation. This is done by increasing the amount of free amino nitrogen available, which is essential for the metabolism of yeast. Consistent fermentation performance, flavour development, and alcohol yield are all supported by improved nutrient availability. Therefore, product uniformity and reduction in production losses associated with protein instability can be ensured through the application of microbial proteases.

Application in the Textile Industry

In the textile industry, microbial proteases are used for biopolishing and surface modification of natural fibres like wool and silk. Fibre damage and the generation of environmentally hazardous effluence can often occur during traditional chemical treatments. Biopolishing done with the aid of microbial proteases selectively removes protruding fibres and impurities found on the surface, resulting in smoother fabrics which have improved softness, lustre and also resistance to piling (Song *et al.*, 2023). Superior process control and reduced environmental impact can be guaranteed by enzymatic textile processing. Microbial proteases operate under mild conditions, minimising the degradation of fibre while also enhancing the quality of the fabric. This makes them attractive for sustainable textile manufacturing.

Medical and Pharmaceutical Applications of Microbial Proteases

As a result of their high specificity, controllable activity, and compatibility with biological systems, microbial proteases have become increasingly important in medical and pharmaceutical systems. Microbial proteases selectively act on protein substrates. This minimises damage to the tissues surrounding it and also reduces adverse side effects, unlike chemical agents. Their sustainability for therapeutic and clinical applications is further enhanced by their degradability and biocompatibility. Advancements in the purification of enzymes, stabilisation and immobilisation have expanded the applications of these microbial proteases in modern medicine. Proteases are applied in wound care, drug development and diagnostics (Borges *et al*., 2024; Putri, 2024; Rai *et al*., 2024; Eskilson *et al*., 2025; Jamal *et al*., 2025). Microbial proteases are useful in pharmaceutical biotechnology. They have been used as therapeutic agents, diagnostic tools, and biocatalysts for drug formulation. A growing number of healthcare systems favour enzyme-targeted interventions that are beneficial, targeted, and environmentally friendly. This has increased the significance of microbial proteases (Jamal *et al*., 2025).

Application in Wound Debridement and Healing

Microbial proteases are useful in medicine in wound debridement and healing. Wound debridement is a method that involves the removal of necrotic (dead) tissue from a wound, especially a surgical wound, to prevent infection while also promoting the regeneration of the tissues (Putri, 2024). Traditional surgical methods for debridement are invasive, painful, and capable of causing harm to the patients. Thus, microbial proteases used in enzymatic debridement are safer and more selective alternatives (Putri, 2024; Jamal *et al*., 2025). The protease enzymes of microbes hydrolyse the native and necrotic proteins found in wound exudates. They accomplish it without a negative impact on healthy tissues, thereby establishing a good condition for the proliferation of cells, angiogenesis, and granulation tissue. The treatment by microbial proteases enhances the healing process, particularly in long-lasting wounds such as diabetic ulcers, pressure sores, and burns. In addition to this, inflammation is reduced by enzymatic debridements, therefore reducing the need for frequent surgical processes. Incorporating microbial proteases into wound dressings and gels has brought about improvements to patients' comfort and clinical outcomes (Ghoreishi *et al*., 2021; Putri, 2024).

Application in Antimicrobial and Antibiofilm Activities

Antimicrobial and anti-glycoprotein properties are important in addressing antibiotic resistance. These properties are exhibited by microbial proteases. Biofilms are structured microbial communities which are found in an extracellular polymeric matrix. The pathogens protect themselves from antibiotics and also from the host's responses. They are responsible for repeated infections, which are most often linked to chronic wounds in implanted medical devices and also hospital-acquired infections (Putri, 2024; Eskilson *et al*., 2025; Jamal *et al*., 2025). Microbial proteases can degrade biofilms; they do this by breaking down the protein components of the extracellular polymeric matrix, therefore destabilising the structure of the biofilm. This process exposes the microorganisms, making them more susceptible to antimicrobial agents. As a result, these microbial proteases make antibiotics more effective when used in combination therapies (Ghoreishi *et al*., 2021). Other than the disruption of biofilm, some microbial proteases can cause direct damage to microbial cell walls and membranes. This makes the pathogenic bacteria less viable. As a result of this, proteases have become promising candidates for the control of infection, sanitation of medical devices and also the development of antimicrobial formulations, resulting in the reduction of reliance on conventional antibiotics (Jamal *et al*., 2025).

Application in Drug Development and Diagnostics

Microbial proteases are very important in pharmaceutical research, the development of drugs, and diagnosis. Proteases have been used for the characterisation of proteins, synthesis of peptides and also structure-function studies in drug discovery. The ability to break down proteins at specific sites aids molecular modifications, which is important for understanding the mechanisms of diseases and therapeutic targets. In diagnostics, proteases are found to be employed in the production of acids used to detect disease biomarkers by selectively processing the proteins being targeted. This results in an enhancement of diagnostic accuracy and sensitivity, especially in enzyme-linked immunoassays and proteomic analysis. Proteases are also used in the activation of prodrugs, where inactive compounds are converted into pharmacologically active forms through enzymatic cleavage. This improves the efficiency of drugs and reduces systemic toxicity.

Application in Therapeutic and Enzyme Replacement Therapy

Microbial proteases are becoming more explored in their usage as therapeutic enzymes for the treatment of disorders which are associated with abnormal protein accommodation or impaired proteolytic activity. Enzyme replacement therapy involves supplementing enzymes which are not functioning properly to bring back normal physiological function. Advancements in the formulation of enzymes, encapsulation, and delivery systems have resulted in enhanced stability and bioavailability. Microbial proteases have expanded their therapeutic potential through these advancements (Adetunji *et al*., 2023; Putin, 2024; Jamal *et al*., 2025; Suresh & Vaithilingam, 2025). Advantages like scalability, cost-effectiveness, and reduction in risk of pathogenic transmission are offered by the use of microbial enzymes when compared to animal-derived enzymes.

Agricultural and Feed Applications of Microbial Proteases

Microbial proteases have been widely adopted in the agricultural sector. They are found to be useful in the improvement of animal nutrition, feed efficiency and also promotion of sustainable farming practices. Protein is known to be a major component of animal feed. It is, however, costly, and inefficient utilisation can result in economic losses and pollution of the environment. The supplementation of protein with proteases addresses these challenges by increasing protein digestibility and absorption of nutrients (Ojo-Omoniyi *et al.*, 2024).

Application in Animal Feed Supplementation

Microbial proteases are widely used in the formulation of animal feeds. They improve the breakdown of complex dietary proteins into amino acids and peptides, which can be easily absorbed. Protease aids in the enhancement of feed conversion efficiency, growth performance, and overall animal health. The amount of undigested protein which is excreted in animal waste is reduced by efficient protein utilisation, which lowers nitrogen pollution in the agricultural environment (Ojo-Omoniyi *et al.*, 2024). Using microbial proteases as supplements is especially beneficial to poultry and aquaculture; this is because the secretion of enzymes may be insufficient to fully make use of plant-based protein sources. Microbial proteases contribute to improvement in productivity by making up for these limitations.

Application in the Enhancement of Nutrient Digestibility

Food ingredients which are derived from plants most often contain anti-nutritional factors, which are known to interfere with the digestion of protein and absorption of nutrients. Microbial proteases break down these inhibitory compounds, therefore making the nutrients readily available. Improving digestion results in a better growth rate, better new function and a reduction in the need for formulation of feeds with high protein (Adetunji *et al.*, 2023). The reduction in the excretion of nitrogen, which results from improved digestibility, also contributes to the sustainability of the environment by reducing ammonia emissions as well as the contamination of groundwater, which is associated with livestock farming.

Application in Plant Disease Control

Microbial proteases play important roles in the control of plant disease. They do so by breaking down pathogenic proteins and inhibiting the virulence mechanisms of microbes. Some proteases are known to interfere with pathogen attachments, penetration, and colonisation of the tissues of plants. This results in a reduction of diseases. Application of microbial protease supports the integration of pest management strategies and also reduces total dependence on chemical pesticides (Ferreira & Soares, 2023; Areej *et al.*, 2024). The use of microorganisms which produce proteases as biological control agents is a sustainable step towards crop protection, which aligns with eco-friendly agricultural practices.

Environmental and Biotechnological Applications of Microbial Proteases

The activity of microbial proteases to break down waste and pollutant which are rich in protein makes them important players in environmental biotechnology. An increase in the regeneration of organic waste as a result of industrialisation and population growth has necessitated efficient and sustainable waste management strategies. Microbial proteases offer environmentally safe solutions through biological degradation processes, which have a positive effect on the environment (Adetunji *et al.*, 2023).

Application in Waste Management and Bioremediation

Microbial proteases can be used effectively for the treatment of the potential wastes from food processing, slaughterhouses and agricultural industries. The breakdown of waste by enzymes reduces its volume, smell, and pathogen load, as well as converting this waste into simpler compounds that can be processed and recycled. The principle of a circular bioeconomy is supported by converting waste into products that create value, such as animal feed and fertilisers (Adetunji *et al.*, 2023).

Application in Treatment of Protein-Rich Industrial Effluents

Effluents from industries such as dairy, meat processing and pharmaceuticals, which are rich in protein, pose significant environmental problems because they have a high organic load. The use of microbial proteins in wastewater treatment enhances the breakdown of organic matter, resulting in a reduction of chemical oxygen demand, thereby improving the quality of effluent. Enzymatic methods of waste treatment are much safer when compared to chemical treatment methods; they are also more environmentally sustainable (Reddy *et al.*, 2022).

Application in the Recycling of Keratinous and Protein Wastes

Waste such as feathers, hair, wood and horns, which contain keratin, are most often resistant to conventional degradation. This is because they have a more stable protein structure. Some specialised microbial proteases can effectively hydrolyse keratin by converting these waste materials into protein and amino acids, which can be easily digested. These hydrolysates are important in animal feed, fertilisers, and also in industrial raw materials, resulting in a reduction of environmental pollution and promotion of waste valorisation (Song *et al.*, 2023).

Conclusion

Microbial proteases are one of the most versatile and economically important groups of enzymes in modern biotechnology. The diversity of microorganisms which can produce these proteases, ranging from bacteria and fungi to actinomycetes, shows that microbial systems present a large potential. The ability to function under a wide range of environmental conditions, which include extreme pH, temperature, and salinity, makes them suitable for complex industrial processes. The adoption of submerged and solid-state fermentation processes shows a sustainable and environmentally responsible bioprocessing. Traditionally, this improvement in purification, immobilisation, and stabilisation methods has increased the practical applicability of these enzymes, thereby improving operational stability.

In the industrial sector, the application of proteases has modified the processes of making detergents, leather, food, beverages, and textiles by replacing chemicals with ecological alternatives. Microbial proteases have extreme potential in different areas of medicine and pharmaceuticals. They can be used as wound care agents, antimicrobial agents, diagnostic agents, and therapeutic agents. In agriculture, proteases contribute to enhancing how animals utilise their feed and disease control, while in environmental management, they deal with the treatment of toxic waste and bioremediation.

Research must be directed towards screening more microbial sources, particularly from less-explored environments such as extreme habitats and peculiar ecological niches, in view of the increasing importance of microbial proteases. Additional investment in genetic engineering and protein engineering strategies aimed at improving enzyme performance in terms of specificity and resistance to industrial stress factors is recommended.

References

Adetunji, A. I., Olaitan, M. O., Erasmus, M., & Olaniran, A. O. (2023). Microbial proteases: A next generation green catalyst for industrial, environmental and biomedical sustainability. *Food Materials Research, 3*, Article 12. https://doi.org/10.48130/FMR-2023-0012

Areej, A., Usama, M., Zulfiqar, U., Sarwar, F., Maryam, & Ashiq, A. (2024). Biopesticides in sustainable agriculture: Enhancing targeted pest control and ecosystem health. *Applied Agriculture Sciences, 2*(1), 1–8. https://doi.org/10.25163/agriculture.2110006

Aruna, V., Chandrakala, V., Angajala, G., & Nagarajan, E. R. (2023). Proteases: An overview on recent industrial developments and current scenario in the revolution of biocatalysis. *Materials Today: Proceedings, 92*, 565–573. https://doi.org/10.1016/j.matpr.2023.03.806

Ashaolu, T. J., Malik, T., Soni, R., Prieto, M. A., & Jafari, S. M. (2024). Extremophilic microorganisms as a source of emerging enzymes for the food industry: A review. *Food Science & Nutrition, 13*(1), e4540. https://doi.org/10.1002/fsn3.4540

Borges, P. H. O., Ferreira, S. B., & Silva, F. P. (2024). Recent advances on targeting proteases for antiviral development. *Viruses, 16*(3), Article 366. https://doi.org/10.3390/v16030366

Elshazly, R. G., Sobieh, S. S., Zaki, S. S., & Abdel Tawab, S. A. F. (2022). Cell progression of biofilm formation in *Candida albicans* and estimation of aspartic proteinase activity. *Journal of Scientific Research in Science, 39*(2), 130–147. https://doi.org/10.21608/jsrs.2022.275792

Eskilson, O., Wiman, E., Reustle, N., Langwagen, J., Sotra, Z., Svärd, A., Selegård, R., Baş, Y., Berglund, L., Oksman, K., Bengtsson, T., Junker, J. P. E., Khalaf, H., & Aili, D. (2025). Nanocellulose wound dressings with integrated protease sensors for detection of wound pathogens. *ACS Sensors, 10*(6), 3953–3963. https://doi.org/10.1021/acssensors.4c03428

Fasiku, S. A., Ogunsola, O. F., Fakunle, A., & Olanbiwoninu, A. A. (2020). Isolation of bacteria with potential of producing extracellular enzymes (amylase, cellulase and protease) from soil samples. *Journal of Advances in Microbiology, 20*(3), 21–26. https://doi.org/10.9734/jamb/2020/v20i330224

Fasiku, S. A., Bello, M. A., & Odeniyi, O. A. (2023). Production of xylanase by *Aspergillus niger* GIO and *Bacillus megaterium* through solid-state fermentation. *Access Microbiology, 5*(6), 000506.v5. https://doi.org/10.1099/acmi.0.000506.v5

Fortuna, A., Collalto, D., & Rampioni, G. (2024). Assays for studying *Pseudomonas aeruginosa* secreted proteases. In G. Bertoni & S. Ferrara (Eds.), *Pseudomonas aeruginosa* (pp. 137–151). Humana. https://doi.org/10.1007/978-1-0716-3473-8_10

Gandía, M., & Garrigues, S. (2024). Filamentous fungi as excellent industrial strains: Development and applications. *Journal of Fungi, 10*(8), Article 541. https://doi.org/10.3390/jof10080541

Ghoreishi, F. S., Roghanian, R., & Emtiazi, G. (2022). Novel chronic wound healing by anti-biofilm peptides and protease. *Advanced Pharmaceutical Bulletin, 12*(3), 424–436. https://doi.org/10.34172/apb.2022.047

Jamal, G. A., Jahangirian, E., Hamblin, M. R., Mirzaei, H., Tarrahimofrad, H., & Alikowsarzadeh, N. (2025). Proteases, a powerful biochemical tool in the service of medicine, clinical and pharmaceutical. *Preparative Biochemistry & Biotechnology, 55*(1), 1–25. https://doi.org/10.1080/10826068.2024.2364234

Jayashree, S. J., & Pan, I. (2025). Quantitative estimation of protease production in liquid culture medium supplemented with casein, gelatin and skim milk for 2 days by measuring optical density. *AIP Conference Proceedings, 3300*(1), 020224. https://doi.org/10.1063/5.0277694

Khan, Z., Shafique, M., Jabeen, N., Naz, S. A., Yasmeen, K., Ejaz, U., & Sohail, M. (2023). Protease from *Bacillus subtilis* ZMS-2: Evaluation of production dynamics through response surface methodology and application in leather tannery. *Journal of King Saud University - Science, 35*, Article 102643. https://doi.org/10.1016/j.jksus.2023.102643

Khatami, K., Qazanfarzadeh, Z., & Jiménez-Quero, A. (2026). Fungal fermentation: The blueprint for transforming industrial side streams and residues. *Bioresource Technology, 440*, Article 133426. https://doi.org/10.1016/j.biortech.2025.133426

Kotb, E., Alabdalall, A. H., Alsayed, M. A., Alghamdi, A. I., Alkhaldi, E., AbdulAzeez, S., & Borgio, J. F. (2023). Isolation, screening, and identification of alkaline protease-producing bacteria and application of the most potent enzyme from *Bacillus* sp. Mar64. *Fermentation, 9*(7), Article 637. https://doi.org/10.3390/fermentation9070637

Kumar, A., Dhiman, S., Krishan, B., Samtiya, M., Kumari, A., Pathak, N., Kumari, A., Aluko, R. E., & Dhewa, T. (2024). Microbial enzymes and major applications in the food industry: A concise review. *Food Production, Processing and Nutrition, 6*, Article 85. https://doi.org/10.1186/s43014-024-00261-5

Latha Ravi, J., Ghosh, P., Ahmad, F., Haque, S., Barciela, P., Chamorro, F., Jorge, A. O. S., Prieto, M. A., & Rana, S. S. (2025). Microbial conversion of vegetable waste for flavor additives via solid-state fermentation: A comprehensive review. *Frontiers in Nutrition, 12*, Article 1445189. https://doi.org/10.3389/fnut.2025.1445189

Lutpiatina, L., Dwiyanti, R. D., Insana, A., Rizal, M., & Mufid, M. (2025). Antithrombotic activity and hemolysis pattern of fibrinolytic protease-producing bacterial isolates from the coast of Tanjung Dewa, South Kalimantan. *Medical Laboratory Technology Journal, 11*(2), 235–248. https://doi.org/10.31964/mltj.v11i2.689

Moonnee, Y. A., Foysal, M. J., Hashem, A., & Miah, M. F. (2021). Keratinolytic protease from *Pseudomonas aeruginosa* for leather skin processing. *Journal of Genetic Engineering and Biotechnology, 19*(1), Article 53. https://doi.org/10.1186/s43141-021-00149-8

Ojo-Omoniyi, O. A., Moro, D. D., & Afolabi, O. B. (2024). Microbial proteases: Sources, significance and industrial applications. *International Journal of Current Microbiology and Applied Sciences, 13*(6), 1–23. https://doi.org/10.20546/ijcmas.2024.1306.001

Oke, M. A., Ojo, S. A., Fasiku, S. A., & Adebayo, E. A. (2023). Nanotechnology and enzyme immobilization: A review. *Nanotechnology, 34*(38), 385101. https://doi.org/10.1088/1361-6528/acda35

Putri, Y. S. K. (2025). Protease enzyme producing microorganisms and their application in disinfection of infected wounds. *Dinasti Health and Pharmacy Science, 2*(2), 37–42. https://doi.org/10.38035/dhps.v2i2.1822

Rai, P., Hoba, S. N., Buchmann, C., Subirana-Slotos, R. J., Kersten, C., Schirmeister, T., Endres, K., Bufe, B., & Tarasov, A. (2024). Protease detection in the biosensor era: A review. *Biosensors and Bioelectronics, 244*, Article 115788. https://doi.org/10.1016/j.bios.2023.115788

Reddy, N., Deekonda, V., Seshagiri, S., Reddy, R., & Gangula, A. K. (2022). Production, characterization and applications of proteases produced by *Bacillus licheniformis*, *Acinetobacter pittii* and *Aspergillus niger* using neem seed oil cake as the substrate. *Industrial Crops and Products, 187*, Article 115403. https://doi.org/10.1016/j.indcrop.2022.115403

Salas-Bruggink, D. I. J., Sánchez-San Martín, J., Leiva, G., & Blamey, J. M. (2024). Extremozymes: Challenges and opportunities on the road to novel enzymes production. *Process Biochemistry, 143*, 323–336. https://doi.org/10.1016/j.procbio.2024.04.035

Solanki, P., Putatunda, C., Kumar, A., Bhatia, R., & Walia, A. (2021). Microbial proteases: Ubiquitous enzymes with innumerable uses. *3 Biotech, 11*(10), Article 428. https://doi.org/10.1007/s13205-021-02928-z

Song, P., Zhang, X., Wang, S., Xu, W., Wang, F., Fu, R., & Wei, F. (2023). Microbial proteases and their applications. *Frontiers in Microbiology, 14*, Article 1236368. https://doi.org/10.3389/fmicb.2023.1236368

Suresh, A., & Vaithilingam, M. (2025). Microbial proteases as emerging anti-inflammatory therapeutics: A comprehensive review. *Archives of Microbiology, 207*(9), Article 229. https://doi.org/10.1007/s00203-025-04409-w

Umay, B., Gül, A., & Tanyıldızı, M. Ş. (2023). Isolation, identification, and optimization of the fibrinolytic protease-producing strains. *Archives of Microbiology, 205*, Article 135. https://doi.org/10.1007/s00203-023-03486-z

Yang, Z., Huang, Z., Wu, Q., Tang, X., & Huang, Z. (2023). Cold-adapted proteases: An efficient and energy-saving biocatalyst. *International Journal of Molecular Sciences, 24*(10), Article 8532. https://doi.org/10.3390/ijms24108532

Yao, H., Liu, S., Liu, T., Ren, D., Zhou, Z., Yang, Q., & Mao, J. (2023). Microbial-derived salt-tolerant proteases and their applications in high-salt traditional soybean fermented foods: A review. *Bioresources and Bioprocessing, 10*, Article 82. https://doi.org/10.1186/s40643-023-00704-w

Zhou, C., Qin, H., Chen, X., Zhang, Y., Xue, Y., & Ma, Y. (2018). A novel alkaline protease from alkaliphilic *Idiomarina* sp. C9-1 with potential application for eco-friendly enzymatic dehairing in the leather industry. *Scientific Reports, 8*, Article 16467. https://doi.org/10.1038/s41598-018-34416-5