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.v4i1.8137

Applications of Microbial Enzymes in Industries

Samuel Adedayo Fasiku[1], Femi Johnson Afolabi[2],
Tawakalit Adeola Egbeleke[3], Racheal Oluwayemisi Fashogbon[4]
[1,2,4]Ajayi Crowther University, Oyo-Town, Nigeria
[3]Oyo State Ministry of Health, Ibadan, Nigeria
Samfash4@yahoo.com

Article Info:

Submitted:	Revised:	Accepted:	Published:
Nov 27, 2025	Dec 25, 2025	Jan 20, 2026	Jan 28, 2026

Abstract

Microbial enzymes, produced by microorganisms such as bacteria, fungi, and algae, have emerged as indispensable biocatalysts across multiple industrial sectors due to their efficiency, versatility, and activity under diverse environmental conditions. This review aims to highlight the major industrial applications of microbial enzymes and synthesize evidence on their functional roles in contemporary bioprocesses. More than 80 published articles, textbooks, and newsletters were retrieved from reputable platforms, of which approximately 50 were selected for detailed analysis based on relevance and quality. The reviewed literature shows that enzymes now play critical roles in everyday life, with broad applications in medicine, pharmacy, environmental remediation, food processing, detergent manufacture, and energy production. In the detergent industry, amylases, lipases, and proteases are used to break down starch, fats, oils, and proteins, thereby enhancing washing efficiency. In the food sector, microbial enzymes support milk hydrolysis in cheese production, contributing to characteristic flavour development, and are widely employed in fruit juice clarification. In the energy sector, cellulases, xylanases, and lignin-degrading enzymes enable the breakdown of lignocellulosic substrates to release reducing sugars for biofuel production. Medically, L-asparaginase has been used in the treatment of leukaemia, while laccases are applied in the degradation of dyes and the reduction of chemical waste in environmental applications. The diversity of microbial sources allows these enzymes to function under extreme conditions, expanding their usability across varied industrial environments. Overall, the review concludes that microbial enzymes have extensive and growing industrial relevance, underscoring the need for continued research and development to optimize their production, stability, and application in sustainable biotechnological processes.

Keywords: Microbial Enzymes; Industrial Applications; Biocatalysis; Food and Detergent Industries; Biofuel Production.

Introduction

Microbial enzymes are proteinaceous substances produced by microorganisms which speed up the rate of reaction. These enzymes are highly specific, efficient, and capable of functioning under a wide range of environmental conditions (Fasiku *et al.*, 2023a). These conditions include varying pH and temperature, thereby making them highly valuable in industrial applications (Fasiku *et al.*, 2023a). Bacteria and fungi are involved in the production of microbial enzymes (Olanbiwoninu and Fasiku, 2015; Fasiku *et al.*, 2020; Wakil *et al.*, 2020; Fasiku *et al.*, 2023a). Easy production of microbial enzymes makes them scalable and hence a preferable option to enzymes derived from plant and animal sources (Adrio and Demain, 2014). Examples of microbial enzymes are amylases (Fasiku *et al.* 2020), lipases (Abdelaziz *et al.*, 2025), laccases (Fasiku *et al.*, 2023b), phytases (Zhang *et al.*, 2025), xylanases (Fasiku *et al.*, 2023a), cellulases (Onilude *et al.*, 2015), lignases (Fasiku *et al.* 2023b), tannase (Wakil *et al.*, 2020), and others. Microbial enzymes serve various functions and applications in the industries (Chapman *et al.*, 2018).

Fermentation techniques are used in the production of microbial enzymes. During the fermentation process, microorganisms are cultured in a controlled environment to produce enzymes. This is followed by the recovery of enzymes and their applications (Raveendran *et al.*, 2018). Advancements have been made in biotechnology such that microbes can be genetically modified to give a higher yield of enzymes.

Microbial enzymes are applied in the baking and starch processing industries. Starches are hydrolysed into fermentable sugars by amylases, thereby improving the consistency and softness of bread. This increases the volume of bread and also increases its shelf life by preventing staling (Raveendran *et al*., 2018). Hydrolysis of milk protein is carried out by proteases, which accelerate the ripening process of cheese and enhance its flavour profiles (Raveendran *et al*., 2018). The hydrolysis of milk fats by lipases contributes to the development of characteristic flavours of cheese (Liu and Kokare, 2017). Amylase, cellulase and pectinase are involved in the clarification of fruit juice (Ozyilmaz and Gunay, 2023). L-asparaginases have been utilised in the treatment of leukaemia.

Microbial enzymes such as amylase, lipase, protease and others are used in detergent-producing industries. Amylase removes starch-based stains, thereby ensuring effective cleaning in laundry and dishwashing (Raveendran *et al*., 2018). Lignin-degrading enzymes are used in breaking down lignin in lignocellulosic substrates, thereby allowing cellulase and other enzymes to gain access to cellulose and the hemicellulose parts, releasing fermentable sugar for biofuel production (Fasiku *et al.* 2023b; 2023c). Laccases degrade organic pollutants, such as dyes and phenols, found in wastewater during bioremediation (Sharma *et al*., 2020). This review investigated the applications of microbial enzymes in industries.

Sources of Microbial Enzymes

Bacteria, fungi and microalgae are utilised in the production of microbial enzymes (Vingiani *et al*., 2019; Fasiku *et al*., 2023a). Microorganisms are screened for their ability to produce the enzyme of choice before they are selected for the production of the interested enzymes (Fasiku *et al*., 2020; Fasiku *et al*., 2023b). The same enzyme from different microorganisms might not have the same potential. The source of enzymes is important in the characterisation of microbial enzymes. While some enzymes might be active in extreme conditions, others will not. The stability, effectiveness and yield of enzymes are organism-dependent (Fasiku *et al*., 2023a).

Many bacteria have been used in the production of enzymes. Their short generation time, easy manipulation of their genetic makeup and their diversity gave them preference over non-microbial enzymes. Some bacteria that have been widely utilised in producing enzymes are *Bacillus*, *Escherichia*, *Streptomyces*, *Lactobacillus*, *Clostridium*, and *Pseudomonas* species. *Bacillus* species have been known for their ability to produce a variety of enzymes (Fasiku *et al*., 2020). For instance, Fasiku *et al*. (2023a) produced xylanase with *Bacillus megaterium*. *Bacillus subtilis* has been used in the production of many enzymes, such as amylase (Mageed *et al*., 2023), protease (Mahmoud *et al*., 2021; Khan *et al*., 2023), cellulase (Fouda *et al*., 2023), and tannase (Govindarajan *et al*., 2025). The production of protease (Abdella & Ahmed, 2025), amylase (Kholikov *et al*., 2025), Cellulase (Shyaula *et al*., 2023) and other enzymes has been carried out with *Bacillus licheniformis*.

Escherichia coli is used for the production of recombinant enzymes due to its genome, which is well characterised, in addition to easy genetic manipulation (Adrio and Demain, 2014). Therapeutic enzymes such as L-asparaginase (Lefin *et al*., 2025), urate oxidase (Zhao *et al*., 2022), glucarpidase (Vakili *et al*., 2021), and hyaluronidase (Avsharian *et al*., 2024) are produced by *Escherichia coli*. *Lactobacillus* species belong to the group of lactic acid bacteria and produce enzymes (proteases and lactases) that are crucial in the fermentation of dairy products such as yoghurt and are also important in the production of cheese (Zhang *et al*., 2024). Enzymes produced by *Lactobacillus* species during fermentation improve the flavour and texture of products in the food industry.

Several fungi have been reported in the production of various enzymes. *Pleurotus* spp., *Aspergillus* spp., *Lentinus* spp., *Trichoderma* spp., *Penicillium* spp., *Phanerochaete* spp., *Rhizopus* spp., *Mucor* spp., *Saccharomyces* spp. and *Trichoderma* spp. are some of the fungi that have been utilised for the production of different enzymes (Fasiku *et al*., 2023a; Fasiku *et al*., 2023b; Afolabi *et al*., 2024; Struszczyk-Swita *et al*., 2024; Wang *et al*., 2024; Zhao *et al*., 2024; Ricaczeski *et al*., 2025). Microalgae grow rapidly and produce enzymes that are important for biotechnological use (Vingiani *et al*., 2019). Some of the microalgae that have been reported in the production of enzymes are *Phaeodactylum* spp., *Chlorella* spp., *Chlamydomonas* spp., *Nannochloropsis* spp., *Ostreococcus* spp., *Thalassiosira* spp., *Fistuifera* spp., *Dunaliella* spp. *Pseudo-nitzschia* spp., *Karenia* spp., *Tetraselmis* spp., *Haematococcus* spp., *Amphidinium* spp., *Gamberdiscus* spp., *Trebouxia* spp., *Selenastrum* spp. and *Azadinum* spp. (Vingiani *et al*., 2019). Some enzymes and their sources are shown in Table 1.

Table 1: Microbial enzymes and their sources

Enzymes	Source	References
Xylanase	*Bacillus megaterium*	Fasiku *et al.*, 2023a
	Aspergillus niger GIO	Fasiku *et al.*, 2023a
	Lentinus squarrosulus, *Pleurotus ostreatus*	Fasiku *et al.*, 2023b
Cellulase	*Lentinus squarrosulus*, *Pleurotus ostreatus*	Fasiku *et al.*, 2023b
	Bacillus species	Fasiku *et al.*, 2020; Olanbiwoninu *et al.*, 2022
	Bacillus licheniformis	Shyaula *et al.*, 2023
	Torulopsis sphaerica, *Candida krusei*, *Candida utilis*, *Kloeckera apiculata*, *Pichia canadensis*, *Rodotorula rubra*	Onilude *et al.*, 2015
	Bacillus subtilis F3	Fouda *et al.*, 2023
Lipase	*Bacillus* species	Olanbiwoninu *et al.*, 2022
	Bacillus subtilis, *Pseudomonas aeruginosa*	Abubakar *et al.*, 2024
Laccase	*Lentinus squarrosulus, Pleurotus tuber-regium, Pleurotus ostreatus*	Fasiku *et al.*, 2023b
Lignase	*Lentinus squarrosulus, Pleurotus tuber-regium, Pleurotus ostreatus*	Fasiku *et al.*, 2023b
Tannase	*Aspergillus japonicus*, *A. tamarii* and *Neosartorya fumigate*	Wakil *et al.*, 2020
	Bacillus subtilis KMS2-2	Govindarajan *et al.*, 2025
Protease	*Bacillus* species	Fasiku *et al.*, 2020; Olanbiwoninu *et al.*, 2022
	Bacillus subtilis	Mahmoud *et al.*, 2021; Khan *et al.*, 2023
Amylase	*Bacillus* species	Fasiku *et al.*, 2020; Olanbiwoninu *et al.*, 2022
	Bacillus subtilis, *Aspergillus niger*	Mageed *et al.*, 2023
	Bacillus licheniformis 104.K	Kholikov *et al.*, 2025

Classification of Microbial Enzymes

Microbial enzymes can be classified based on their catalytic functions as defined by the Enzyme Commission (EC) system, which organises enzymes into six different classes.

These classes are oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases (Robinson, 2015). Through this system, industries can select enzymes with specific activities. Hydrolases are the most used enzymes as a result of their ability to efficiently break down complex substrates.

Hydrolases are enzymes which break down large molecules into smaller ones with the addition of water. Examples are proteases, amylases, lipases, and cellulases. They play important roles in the digestion of food. They are also involved in cellular signalling and different metabolic reactions taking place in the cells. Proteases are known to hydrolyse peptide bonds; hence, they play an important role in detergents by removing stains which are protein-based, like blood and food (Fasiku *et al*., 2020). In the pharmaceutical industry, they are used for synthesising peptides and antibiotics. They are stable and highly specific, making them ideal for industrial-scale applications (Singh *et al*., 2016).

Amylases are known to break down starches into sugars and, hence, are essential for baking as they increase the consistency of the dough. They are also essential in the production of bioethanol. Their versatility extends to the clarification of beverages, like in the production of beer (Raveendran *et al*., 2018). Lipases are known to catalyse lipid hydrolysis and transesterification, which are used in food processing for the enhancement of flavour (e.g., cheese ripening) and in biofuels for the production of biodiesel from vegetable oils (Gurung *et al*., 2013). Cellulases are enzymes which break down cellulose into glucose, which are important for the production of biofuel from lignocellulosic biomass and textile bio-polishing, thereby reducing fabric pilling and improving softness (Sarmiento *et al*., 2015).

Oxidoreductases are enzymes which are involved in oxidation-reduction reactions. They catalyse the oxidation reaction where the electrons tend to travel from one form of a molecule to the other. Laccases belong to this group and catalyse oxidation reactions. Laccases are widely used in bioremediation to break down pollutants (e.g., dyes, phenols) and in the paper industry for lignin breakdown, promoting eco-friendly processes (Sharma *et al*., 2020). The Transferases enzymes help in the transportation of the functional group among acceptors and donor molecules. Glucosyltransferases transfer glycosyl groups, which are used in functional food production to synthesise oligosaccharides with prebiotic properties, enhancing gut health (Liu and Kokare, 2017).

Lyases are involved in the breaking down of large molecules by means other than hydrolysis and oxidation. Pectin lyases and pectate lyases are examples of lyases and can be used in fruit juice clarification, breaking down pectin to improve juice yield and clarity (Chapman *et al.*, 2018). The isomerase enzymes catalyse the structural shifts present in a molecule, thus causing the change in the shape of the molecule. Glucose isomerases are known to convert glucose to fructose, which is essential for the production of high-fructose corn syrup in the food industry (Robinson, 2015). The ligase enzymes are known to catalyse the catalysis of ligation process. Although they are not as common as others, ligases are used in biotechnology for the manipulation of DNA and in the synthesis of complex molecules. They are useful in pharmaceutical applications (Liu and Kokare, 2017).

Applications of Microbial Enzymes in Industries

Enhancement of Industrial Efficiency and Sustainability

Microbial enzymes lower activation energy at various temperatures and pH levels, thereby lowering the cost of operation (Sharma *et al.*, 2020). Microbial enzymes increase reaction rate, for instance, amylases from *Aspergillus oryzae* hydrolyse starch in less than an hour compared to chemical methods, which take a longer time and require higher temperatures (Raveendran *et al.*, 2018). Cellulases derived from *Trichoderma reesei* degraded lignocellulosic biomass into simple sugars that can be fermented into other products. This is particularly useful in the production of biofuel as it resulted in an improvement in the yield when compared to other mechanical methods (Sarmiento *et al.*, 2015).

Microbial enzymes are used in the treatment of industrial wastewater (Pandey *et al.*, 2017). The global demand for greener and cleaner technology is supported by the use of enzymes in the treatment of wastewater. In the production of dairy products, proteases help enhance the texture of the cheese by breaking down the protein in the milk, thereby ensuring consistent quality (Raveendran *et al.*, 2018). Lipases from *Candida rugosa* in the food industry are known to improve the rate of emulsification. This results in prolonged shelf life and enhances the sensory properties of products such as margarine and baked goods (Gurung *et al.*, 2013).

Applications in the Food and Beverage Industry

Microbial enzymes are used in the food and beverage industry to enhance the quality of products, make processing easier and meet the demand of customers for natural and sustainable products. They improve the texture, flavour, and shelf life of products while reducing the cost of production and negative impact on the environment. Starch was hydrolysed into fermentable sugars by amylases obtained from *Aspergillus oryzae*, improving the consistency and softness of bread, thereby increasing the volume of the bread by 10-15% and also extending the shelf life by preventing staling (Raveendran *et al.*, 2018). Xylanases derived from *Bacillus subtilis* broke down hemicellulose in flour, thereby enhancing the elasticity of the dough and also reducing the time taken to mix, which lowers energy costs (Gurung *et al.*, 2013).

Milk protein hydrolysis is facilitated by proteases from *Aspergillus niger* and *Lactobacillus* species, thereby accelerating the ripening process of cheese and enhancing flavour profiles. This reduces maturation time by up to 50% (Raveendran *et al.*, 2018). Lipases from *Rhizopus oryzae* contribute to the development of characteristic cheese flavours, such as in blue cheese, by hydrolysing milk fats into aromatic compounds (Liu and Kokare, 2017). In the same vein, lipase from *Aspergillus niger* reduced the time for ripening of cheese (Abada, 2019). Transglutaminase has been used in protein cross-linking, while proteinases from *Bacillus* and *Aspergillus* species have been employed to reduce the time for cheese ripening (Abada, 2019). Milk coagulation has been achieved by proteinase from *Aspergillus* sp., and catalase is involved in cheese processing. Other enzymes such as amylase, lactase, and rennet are utilised in the dairy industry (Abada, 2019).

Pectinases obtained from *Aspergillus niger* break down pectin in fruit juices. They improve the clarity and yield by 20–30%. This is critical for producing clear apple and citrus juices (Chapman *et al.*, 2018). Many juices, such as banana juice, pear juice, apple juice, orange juice and grape juice, have been clarified with microbial enzymes (Shwe and Win, 2019; Sondhi *et al.*, 2021; Bamigboye *et al.*, 2022; Hossain *et al.*, 2024). β-Glucosidases from *Saccharomyces cerevisiae* enhance wine aroma by releasing volatile compounds from grape glycosides, improving sensory quality (Raveendran *et al.*, 2018).

Applications in the Pharmaceutical and Medical Industry

Microbial enzymes are important in pharmaceutical industries for developing complex drugs, diagnostic tools, and they also enable therapeutic applications. They are highly specific and efficient, making them ideal for precision medicine. Penicillin acylase and peroxidase are utilised in the synthesis of semisynthetic antibiotics and antimicrobials (Liu and Kokare, 2017). Lipase from *Candida rugosa* is used to produce lovastatin, which is capable of reducing the serum content of cholesterol (Shrivastava *et al*., 2019). Nattokinase is a serine proteinase derived from *Bacillus subtilis* and has effect on some of the factors (factor VIII, factor VII and fibrinogen) involved in blood clotting. The use of nattokinase could be regarded as a nutraceutical for cardiac disorders (Shrivastava *et al*., 2019).

L-Asparaginase derived from *Erwinia Chrysanthemi* is known to be used in the treatment of acute lymphoblastic leukaemia by reducing L-asparagine. This results in the inhibition of cancer growth cells with reduced or no side effects (Singh *et al*., 2016). L-asparaginase, urate oxidase, glucarpidase, and hyaluronidase produced by *Escherichia coli* are utilised as therapeutic enzymes (Vakili *et al*., 2021; Zhao *et al*., 2022; Avsharian *et al*., 2024; Lefin *et al*., 2025). Proteases from *Bacillus* species are used in the production of formulations that are used to treat wounds (Chapman *et al*., 2018). Taq polymerase from *Thermus aquaticus* is very important for PCR-based diagnostics. It enables the quick detection of pathogens like SARS-CoV-2 that has high sensitivity. Glucose oxidase derived from *Aspergillus niger* was used in biosensors for monitoring blood glucose levels in diabetic patients and offers accurate and real-time results (Wong *et al*., 2008).

Applications in Textile and Detergent Industry

Microbial enzymes are widely used in the production of textiles and detergents. They are used to improve the quality of products, reduce the impact on the environment and also to enhance the overall efficiency of the process. They offer a sustainable replacement to the traditional chemical processes. In the textile industry, cellulases derived from *Trichoderma reesei* are useful in biopolishing and also in the removal of microfibils from cotton fabrics in order to increase the softness and also the general appearance of the fabric (Cavaco-Paulo, 1998; Araújo *et al*., 2008). *Aspergillus niger* produced pectinases, which could facilitate bio-sourcing. They removed impurities from cotton fibres, thereby improving the uptake of dye and reduces chemical waste (Gurung *et al*., 2013). Laccases of *Trametes versicolor* are used in bleaching denim; they are used to replace harsh chlorine-based agents and also reduce environmental pollution (Sharma *et al*., 2020).

Proteases from *Bacillus subtilis* break down stains, which are protein-based, like blood. They improve cleaning efficiency at lower temperatures, thereby saving energy (Singh *et al*., 2016). Lipases, which are derived from *Candida rugosa,* can target lipid stains, thereby increasing the performance in cold washing water. This aligns with the demand for eco-friendly products by customers (Chapman *et al*., 2018). Amylases remove starch-based stains, thereby ensuring there is effective cleaning in laundry and dishwashing formulations (Raveendran et al., 2018).

Applications in Biofuel and Waste Management

Microbial enzymes are important in the production of biofuel and also in the management of waste. they support the transition to renewable energy and sustainable treatment of waste. Cellulases and hemicellulases derived from *Trichoderma reesei* are known to hydrolyse lignocellulosic biomass into fermentable sugars. This enables the production of bioethanol with yields which are sometimes up to 80% higher than chemical methods (Sarmiento *et al*., 2015). Lignocellulosic substrates treated with *Pleurotus ostreatus*, with the ability to produce cellulase, xylanase and lignin-degrading enzymes, released more reducing sugar for bioethanol production than untreated ones (Fasiku and Wakil, 2021; Fasiku and Wakil, 2022). Lipases derived from *Rhizopus oryzae* can catalyse the transesterification of vegetable oils into biodiesel. This results in a greener and safer alternative to fossil fuels, thereby resulting in the reduction of the emission of greenhouse gases (Gurung *et al*., 2013).

Laccases from *Trametes versicolor* can degrade organic pollutants, such as dyes and phenols that are found in wastewater, therefore achieving up to 90% pollutant removal in the process of bioremediation (Sharma *et al*., 2020). Proteases and cellulases derived from *Bacillus* and *Aspergillus* species enhanced the process of composting by breaking down organic waste, thereby leading to a reduction in the volume of landfills and production of compost that is rich in nutrients (Pandey *et al*., 2016).

Advantages of microbial enzymes

Microbial enzymes are important in modern biotechnology because of the various advantages they possess. The ability of microorganisms to grow rapidly on wastes/ inexpensive substrates reduces the cost of microbial enzymes when compared with enzymes from other sources, such as plants and animals. They are highly specific and effective, and their production can be easily optimised (Fasiku *et al*., 2023a). The diversity of microorganisms also gave their enzymes the ability to function effectively over a wide range of conditions, like pH and temperature. Microbial enzymes are eco-friendly. The use of microbial enzymes applies to diverse industries, and this is due to their range of catalytic functions (Chapman *et al*., 2018).

Challenges of using microbial enzymes

Although microbial enzymes have many advantages, there are challenges with their use. A lot of enzymes lose their ability under harsh conditions like high temperature and extreme pH, which makes them require stabilising techniques such as immobilisation (Oke *et al*., 2023). The cost of purification of microbial enzymes is high, like about 60% of the cost of production goes into downstream processes, which limits scalability for some applications (Pandey *et al*., 2016). There is a possibility of contamination during the production of microbial enzymes. Enzymes which are produced through genetically modified microbes face strict safety and environmental regulations that lead to a delay in market entry in some regions (Wang *et al*., 2020).

Conclusion

The major microorganisms involved in the production of microbial enzymes are *Bacillus*, *Escherichia*, *Streptomyces*, *Lactobacillus*, *Clostridium*, *Pseudomonas*, *Candida*, *Saccharomyces*, *Pichia*, *Torulopsis*, *Kloeckera*, *Rodotorula*, *Lentinus*, *Pleurotus*, *Aspergillus*, *Neosartorya*, and *Chlorella* species. Microbial enzymes such as amylase, cellulase, protease, xylanase, lipase, laccase, tannase, and others are applied in different industries such as food and beverage, pharmaceutical, medical, textile, detergent, biofuel, and waste management.

References

Abada, E. A. (2019). Application of microbial enzymes in the dairy industry. In *Enzymes in Food Biotechnology* (pp. 61–65). https://doi.org/10.1016/B978-0-12-813280-7.00005-0

Abdelaziz, A. A., Abo-Kamar, A. M., Elkotb, E. S., & Al-Madboly, L. A. (2025). Microbial lipases: Advances in production, purification, biochemical characterization, and multifaceted applications in industry and medicine. *Microbial Cell Factories, 24*, 40. https://doi.org/10.1186/s12934-025-02664-6

Abdella, M. A., & Ahmed, S. A. (2025). Stable protease from Bacillus licheniformis-MA1 strain: Statistical production optimization, kinetic and thermodynamic characterization, and application in silver recovery from used X-ray films. *Microbial Cell Factories, 24*(1), 98. https://doi.org/10.1186/s12934-025-02706-z

Abubakar, A., Abioye, O. P., Aransiola, S. A., Maddela, N. R., & Prasad, R. (2024). Crude oil biodegradation potential of lipase produced by Bacillus subtilis and Pseudomonas aeruginosa isolated from hydrocarbon contaminated soil. *Environmental Chemistry and Ecotoxicology, 6*, 26–32. https://doi.org/10.1016/j.enceco.2023.12.001

Adrio, J. L., & Demain, A. L. (2014). Microbial enzymes: Tools for biotechnological processes. *Biomolecules, 4*(1), 117–139. https://doi.org/10.3390/biom4010117

Afolabi, F. J., Babaniyi, R. B., Obagunwa, M., Onile, F. O., Ajagun, O. J., & Fasiku, S. A. (2024). Ethnomycology of Pleurotus tuber-regium and its use in food, medicine and bioremediation. *Botanica, 30*(4), 183–192. https://doi.org/10.35513/Botlit.2024.4.7

Araújo, R., Casal, M., & Cavaco-Paulo, A. (2008). Application of enzymes for textile fibres processing. *Biocatalysis and Biotransformation, 26*(5), 332–349. https://doi.org/10.1080/10242420802390457

Avsharian, L. C., Loganathan, S., Ebelt, N. D., Shalamzari, A. F., Munoz, I. R., & Manuel, E. R. (2024). Tumor-colonizing E. coli expressing both collagenase and hyaluronidase enhances therapeutic efficacy of gemcitabine in pancreatic cancer models. *Biomolecules, 14*(11), 1458. https://doi.org/10.3390/biom14111458

Bamigboye, C. O., Okonji, R. E., Oluremi, I. O., & James, V. (2022). Stain removing, juice-clarifying, and starch liquefying potentials of amylase from Pleurotus tuberregium in submerged fermentation system. *Journal of Genetic Engineering and Biotechnology, 20*, 23. https://doi.org/10.1186/s43141-022-00298-4

Cavaco-Paulo, A. (1998). Mechanism of cellulase action in textile processes. *Carbohydrate Polymers, 37*(3), 273–277. https://doi.org/10.1016/S0144-8617(98)00070-8

Chapman, J., Ismail, A. E., & Dinu, C. Z. (2018). Industrial applications of enzymes: Recent advances, techniques, and outlooks. *Catalysts, 8*(6), 238. https://doi.org/10.3390/catal8060238

Fasiku, S. A., & Wakil, S. M. (2021). Pretreatment of maize straw with Pleurotus ostreatus and Lentinus squarrosulus for bioethanol production using Saccharomyces cerevisiae. *Novel Research in Microbiology Journal, 5*(6), 1480–1493. https://doi.org/10.21608/nrmj.2021.209731

Fasiku, S. A., & Wakil, S. M. (2022). Screening of factors responsible for conversion of maize straw into bioethanol. *Journal of Microbiology, Biotechnology and Food Sciences, 12*(2), e5901. https://doi.org/10.55251/jmbfs.5901

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

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., Wakil, S. M., & Alao, O. K. (2023b). Screening for lignocellulolytic enzymes-producing white rot fungi. *Asian Journal of Research in Botany, 9*(2), 1–7.

Fasiku, S. A., Wakil, S. M., & Alao, O. K. (2023c). Degradation of lignocellulosic substrates by Pleurotus Ostreatus and Lentinus squarrosulus. *The Asia Journal of Applied Microbiology, 10*(1), 10–20. https://doi.org/10.18488/33.v10i1.3354

Fouda, A., Alshallash, K. S., Atta, H. M., Gamal, M. S., Bakry, M. M., Alawam, A. S., & Salem, S. S. (2023). Synthesis, optimisation, and characterisation of cellulase enzyme obtained from thermotolerant Bacillus subtilis F3: An insight into cotton fabric polishing activity. *Journal of Microbiology and Biotechnology, 34*(1), 207–223. https://doi.org/10.4014/jmb.2309.09023

Govindarajan, R. K., Alrefaei, A. F., Almutairi, M. H., Khanongnuch, C., & Lackner, M. (2025). The bio-transformation of green tea infusion with tannase enzymes produced by Bacillus subtilis KMS2-2. *Journal of Food Science and Technology, 62*, 1863–1873. https://doi.org/10.1007/s13197-024-06194-8

Gurung, N., Ray, S., Bose, S., & Rai, V. (2013). A broader view: Microbial enzymes and their relevance in industries, medicine, and beyond. *BioMed Research International, 2013*, 329121. https://doi.org/10.1155/2013/329121

Hossain, K. M., Khan, U., Rahman, S. M. M., & Khan, M. S. (2024). Potential antimicrobial and fruit juice clarification activity of amylase enzyme from Bacillus strains. *Biotechnology Reports, 44*, e00861. https://doi.org/10.1016/j.btre.2024.e00861

Khan, Z., Sharfique, 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*(4), 102643. https://doi.org/10.1016/j.jksus.2023.102643

Kholikov, A., Vokhidov, K., Murtozoyev, A., Toth, Z. S., Nagy, G. N., Vertessy, B. G., & Makhsumkhanov, A. (2025). Characterisation of a thermostable α-amylase from Bacillus licheniformis 104.K for industrial applications. *Microorganisms, 13*(8), 1757. https://doi.org/10.3390/microorganisms13081757

Lefin, N., Miranda, J., Costa, I. M., Reynaldo, A. P., Monteiro, G., Zamorano, M., Pessoa, A., & Farias, J. G. (2025). Optimized amino acid-enhanced medium for efficient L-asparaginase II production in E. coli: From shake flask to bioreactor. *Fermentation, 11*(5), 239. https://doi.org/10.3390/fermentation11050239

Liu, X., & Kokare, C. (2017). Microbial enzymes of use in industry. In *Biotechnology of microbial enzymes: Production, biocatalysis and industrial applications* (pp. 267–298). https://doi.org/10.1016/B978-0-12-803725-6.00011-X

Mageed, B. M., Ali, S. G., Hammouda, O., & Rasian, M. (2023). Optimization of α-amylase activity enzyme produced by Bacillus subtilis and Aspergillus niger. *Egyptian Journal of Chemistry, 66*(3), 421–426. https://doi.org/10.21608/ejchem.2022.136372.6188

Mahmoud, A., Kotb, E., Alqosaibi, A., Al-Karmalawy, A. A., Al-Dhuayan, I. S., & Alabkari, H. (2021). In vitro and in silico characterization of alkaline serine protease from Bacillus subtilis D9 recovered from Saudi Arabia. *Heliyon, 7*, e08148. https://doi.org/10.1016/j.heliyon.2021.e08148

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

Olanbiwoninu, A. A., & Fasiku, S. A. (2015). Production of bacterial amylases and cellulases using sweet potato (*Ipomoea batatas* (L.) Lam.) peels. *African Journal of Biochemistry Research, 9*(9), 104–109. https://doi.org/10.5897/AJBR2015.0841

Onilude, A. A., Adekoya, A. O., Wakil, S. M., Fasiku, S. A., & Ja'afaru, I. M. (2015). Isolation and identification of thermophilic cellulolytic yeast from cassava waste dump. *Journal of Science Research, 14*, 131–143.

Ozyilmaz, G., & Gunay, E. (2022). Clarification of apple, grape and pear juices by co-immobilized amylase, pectinase and cellulase. *Food Chemistry, 398*, 133900. https://doi.org/10.1016/j.foodchem.2022.133900

Pandey, A., Höfer, R., Taherzadeh, M., Nampoothiri, M., & Larroche, C. (2016). *Industrial biorefineries and white biotechnology*. Elsevier. https://doi.org/10.1016/C2013-0-19082-4

Pandey, K., Singh, B., Pandey, A. K., Badruddin, I. J., Pandey, S., Mishra, V. K., & Jain, P. A. (2017). Application of microbial enzymes in industrial waste water treatment. *International Journal of Current Microbiology and Applied Sciences, 6*(8), 1243–1254. https://doi.org/10.20546/ijcmas.2017.608.151

Raveendran, S., Parameswaran, B., Ummalyma, S. B., Abraham, A., Mathew, A. K., Madhavan, A., Rebello, S., & Pandey, A. (2018). Applications of microbial enzymes in food industry. *Food Technology and Biotechnology, 56*(1), 16–30. https://doi.org/10.17113/ftb.56.01.18.5491

Ricaczeski, C., Sallum, E. E., Soccol, C. R., Candeo, E. H., Cerri, M. L., Sydney, E. B., & Pietrobelli, J. M. T. (2025). Optimized production of ligninolytic enzymes by immobilized Phanerochaete chrysosporium in a lab-scale bioreactor. *Preparative Biochemistry and Biotechnology, 55*(8), 1056–1065. https://doi.org/10.1080/10826068.2025.2478408

Robinson, P. K. (2015). Enzymes: Principles and biotechnological applications. *Essays in Biochemistry, 59*, 1–41. https://doi.org/10.1042/bse0590001

Sarmiento, F., Peralta, R., & Blamey, J. M. (2015). Cold and hot extremozymes: Industrial relevance and current trends. *Frontiers in Bioengineering and Biotechnology, 3*, 148. https://doi.org/10.3389/fbioe.2015.00148

Sharma, B., Dangi, A. K., & Shukla, P. (2020). Contemporary enzyme based technologies for bioremediation: A review. *Journal of Environmental Management, 210*, 10–22. https://doi.org/10.1016/j.jenvman.2017.12.075

Shrivastava, A., Shrivastava, N., & Singh, P. K. (2019). Enzymes in pharmaceutical industry. In *Enzymes in Food Biotechnology* (pp. 591–602). https://doi.org/10.1016/B978-0-12-813280-7.00034-7

Shwe, K. K. W., & Win, S. S. (2019). Effect of amylolytic enzyme treatment on banana juice preparation, yield and clarification: A preliminary approach. *International Journal of Science and Engineering Applications, 8*(2), 75–78.

Shyaula, M., Regmi, S., Khadka, D., Pudel, R. C., Dhakal, A., Koirala, D., Sijapati, J., Singh, A., & Maharjan, J. (2023). *International Journal of Microbiology, 2023*(1), 3615757. https://doi.org/10.1155/2023/3615757

Singh, R., Kumar, M., Mittal, A., & Mehta, P. K. (2016). Microbial enzymes: Industrial progress in 21st century. *3 Biotech, 6*(2), 174. https://doi.org/10.1007/s13205-016-0485-8

Sondhi, S., Kaur, P. S., Sura, H., Juglani, M., & Sharma, D. (2021). Amylase based clarification of apple, orange and grape juice. *International Journal of Contemporary Technology and Research, 3*(3), 187–190. https://doi.org/10.46860/cgcijctr.2021.06.31.187

Struszczyk-Swita, K., Kaczmarek, M. B., Antczak, T., & Marchut-Mikolajczyk, O. (2024). Continuous production of chitooligosaccharides in a column reactor by the PUF-immobilized whole cell enzymes of Mucor circinelloides IBT-83. *Microbial Cell Factories, 23*, 258. https://doi.org/10.1186/s12934-024-02529-4

Vakili, O., Khatami, S. H., Maleksaet, A., Movahedpour, A., Fana, S. E., Sadegh, R., Salmanzadeh, A. H., Razeghifam, H., Nourdideh, S., Tehrani, S. S., & Taheri-

Anganeh, M. (2021). Finding appropriate signal peptides for secretory production of recombinant glucarpidase: An in silico method. *Recent Patents on Biotechnology, 15*(4), 302–315. https://doi.org/10.2174/1872208315666210921095420

Vingiani, G. M., Luca, P., Ianora, A., Dobson, A. D. W., & Lauritonao, C. (2019). Microalgal enzymes with biotechnological applications. *Marine Drugs, 17*, 459. https://doi.org/10.3390/md17080459

Wakil, S. M., Ajayi, O. D., & Fasiku, S. A. (2020). Production of tannase by fungi isolated from different soils. *Journal of Basic and Applied Sciences, 16*, 1–8. https://doi.org/10.29169/1927-5129.2020.16.01

Wang, Z., Su, C., Zhang, Y., Shangguan, S., Wang, R., & Su, J. (2024). Key enzymes involved in the utilization of fatty acids by Saccharomyces cerevisiae: A review. *Frontiers in Microbiology, 14*, 1294182. https://doi.org/10.3389/fmicb.2023.1294182

Wong, C. M., Wong, K. H., & Chen, X. D. (2008). Glucose oxidase: Natural occurrence, function, properties and industrial applications. *Applied Microbiology and Biotechnology, 78*(6), 927–938. https://doi.org/10.1007/s00253-008-1407-4

Zhang, K., Tang, H., Farid, M. S., Xiang, F., & Li, B. (2024). Effect of Lactobacillus helveticus exopolysaccharides molecular weight on yogurt gel properties and its internal mechanism. *International Journal of Biological Macromolecules, 262*, 130006. https://doi.org/10.1016/j.ijbiomac.2024.130006

Zhang, L., Song, Z., Guo, J., Liu, W., Li, J., Meng, Q., & Mo, J. (2025). Isolation, identification, and fermentation optimization of phytase-producing bacteria and their effects on soybean seedlings. *Applied Biochemistry and Biotechnology, 197*, 2417–2436. https://doi.org/10.1007/s12010-024-05154-4

Zhao, R., Li, Z., Sun, Y., Ge, W., Wang, M., Liu, H., Xun, L., & Xia, Y. (2022). Engineered Escherichia coli Nissle 1917 with urate oxidase and an oxygen-recycling system for hyperuricemia treatment. *Gut Microbes, 14*(1), 2070391. https://doi.org/10.1080/19490976.2022.2070391

Zhao, S., Zhang, T., Hasunuma, T., Kondo, A., Zhao, X., & Feng, J. (2024). Every road leads to Rome: Diverse biosynthetic regulation of plant cell wall-degrading enzymes in filamentous fungi Penicillium oxalicum and Trichoderma reesei. *Critical Reviews in Biotechnology, 44*(7), 1241–1261. https://doi.org/10.1080/07388551.2023.2280810