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Review

Industrial enzyme production in Bangladesh: current landscape, scope, and challenges

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Abstract: Enzymes are important biological catalysts that perform specialized functions within living organisms. Industrial enzymes are crucial in various sectors, including pharmaceuticals, the textile industry, the manufacturing of chemicals, biodiesel, the food and beverages industry, and consumer goods. Enzymes can be obtained from multiple sources, including microbes, animals, and plants. Microorganisms, especially bacteria and fungi, provide more than 50% of industrial enzymes because of their advantageous growth features, low nutritional needs, and biochemical diversity. Bangladesh's economy relies heavily on agriculture and generates biomass energy from waste such as rice husk, straw, jute sticks, and sugarcane bagasse. To reduce the environmental impact, it is vital to modify these waste materials into beneficial industrial and commercial products, like enzymes. This review article investigates the current landscape, scope, and challenges of industrial enzyme production in Bangladesh. Bangladesh has become an appealing destination for biotech firms due to variables such as yearly bio-product imports, local market consumer demand, and the availability of resources and competent people. In 2021, Bangladesh ranked as the 34th largest importer of enzymes worldwide, with an import value of $47.4 million. Bangladesh mainly imports enzymes from Turkey, Malaysia, China, Singapore, and Sri Lanka. This study identifies a critical research gap, which is the lack of a dedicated industrial enzyme production industry in Bangladesh. This gap is impeding large-scale implementation, despite ongoing research efforts. Furthermore, we suggest the establishment of a specialized industrial enzyme production sector in Bangladesh, which would benefit the environment and promote economic growth through the utilization of agro-industrial waste resources. Finally, this thorough assessment of current industrial enzyme research in Bangladesh seeks to provide researchers and stakeholders with essential information for future development. Collaboration between the government, businesses, and academics is critical to fostering growth and capitalizing on the potential of the worldwide enzyme industry.

Keywords: industrial enzyme; application; research; agro-industrial wastes; governmental support; Bangladesh

1. Introduction

Enzymes are biocatalysts with distinct characteristics, such as the capacity to operate in mild temperatures, utilize renewable resources, and demonstrate exact substrate and product selectivity (Farooq *et al*., 2021). They have recently become an important substitute for traditional chemical catalysts, allowing for the manufacturing of a diverse spectrum of chemicals with high efficiency (Chapman *et al*., 2018; Gupta *et al*., 2019). Pharmaceuticals, the textile industry, chemical manufacture, biofuel generation, food and beverage, and consumer items all use enzymes (Girelli *et al*., 2020). Enzymes play an important part in the manufacture of food and beverages and offer a significant portion of the industrial enzyme market. Enzyme production was revolutionized in the second part of the 20th century with the discovery of fermentation techniques, which made it possible to produce defined-property, purified enzymes in large quantities. Enzymes can be obtained through plant and animal sources as well as fermentation using bacterial or fungal strains. Genetically modified (GM) and wild-type (WT) strains are used to increase protein manufacture and prevent the formation of unwanted secondary metabolites (Deckers *et al*., 2020). Amylase takadiastase was the first enzyme to be synthesized industrially from wheat bran and was utilized as a medicinal agent for digestive diseases in the United States in 1894 (Samanta, 2022).

Enzymes must be inexpensive, highly active, selective, and stable to serve as successful industrial biocatalysts. Recent developments in the field of protein engineering have made it possible to create enzymes that are specifically suited for a range of industrial uses. It is now economically possible to produce enzymes on a big scale using genetic engineering and fermentation technology (Madhavan *et al*., 2021).

Bangladesh is rapidly developing as a result of the country's expanding middle-class population, expanding domestic consumer market, and rising use of digital technology. Industrialization is replacing agriculture as the country's primary income source, with the agricultural sector contributing 14.2% to the economy. In 2018, industrial growth increased by 8.2% YoY (Nomani *et al*., 2022). Bangladesh's GDP increased by 7.1% YoY in June 2022, however, due to disturbances in the global economy, it is predicted to decline to 5.3% in 2023 (ADB, 2023).

Bangladesh's industrial sector is expanding quickly, and the country is facing significant challenges as it moves from being classified as a least developed (LDC) to a developing one in 2026 (Wing, 2022). Despite the increasing demand for industrial enzymes across various sectors, including pharmaceuticals, textiles, and food production, there is currently no well-established enzyme production industry within the country. As a result, Bangladesh heavily relies on imports from other nations like China, Sri Lanka, and Singapore to meet its enzyme needs (IMARC Food Enzymes Market, 2022). This creates an urgent need to develop a domestic enzyme production infrastructure that aligns with the nation's expanding industrial landscape.

We hypothesize that by encouraging the development of a robust domestic enzyme production industry, Bangladesh can not only reduce its dependency on imports but also stimulate economic growth, create employment opportunities, and bolster the country's industrial capabilities. This review aims to investigate the current landscape, scope, and challenges of industrial enzyme production in Bangladesh to support this hypothesis.

To address these issues, our research will seek to answer the following key question: "What are the current conditions, opportunities, and challenges related to industrial enzyme production in Bangladesh, and how can the country establish a self-sufficient enzyme production industry to meet the growing demand?" A collaborative, multidisciplinary approach, as well as government assistance and incentives, are required to provide the groundwork for the large-scale enzyme manufacturing process.

2. Historical background

In the Neolithic settlement of Jiahu in China around 7000 BCE, enzymes were first used to process grains for alcoholic beverage production (Wang *et al*., 2021). Wine manufacturing was first documented around 5400-5000 BCE at the Neolithic settlement of Tepe in Mesopotamia (McGovern *et al*., 2017). For more than 2,500 years, *Aspergillus* strains have been widely used in China as starter cultures to ferment grains, producing rice wine or other distilled products. Similarly, ancient Egyptians have been using microbes and malt in bread production dating back to 2000-1200 BCE (Vogel, 2019). Fungi and bacteria- produced amylases and protease enzymes have become a competitive substitute for those produced from plants and animals. The use of purified proteases has been made for the clarification of beer since 1911, whereas pectinases have previously been employed for wine and juice clarification. The global production of citric acid exceeded one million tons in 2023 and is anticipated to reach $3.2 billion (West, 2023). The incorporation of microbial proteases in detergents is a great achievement in Enzymology. The first batch of *Bacillus* protease was commercialized in 1959 and is currently produced by Novozymes in Denmark as a major industrial product. During the 1960s, microbial enzymes became more widely used in the starch business (Nunes and Kumar, 2018). With the use of contemporary biotechnology methods, the enzyme sector has progressed, increasing output and producing enzymes that are specifically tailored for optimum function.

3. Enzyme types and application

Enzymes have historically been widely employed in the manufacturing of a variety of food and beverage goods, including cheese and dairy products, as well as alcoholic beverages items such as wine and beer, and fermented foods. These enzymes are readily accessible on the market and derived from animals, plants, and microorganisms. Microorganisms, especially bacteria and fungi, provide more than half of industrial enzymes because of their advantageous characteristics. These microorganisms can be efficiently cultivated using fermentation techniques, requiring minimal time and space. Additionally, their high consistency allows for straightforward process modification and optimization (Raveendran *et al*., 2018). Industrial enzymes are classified into three types: technical enzymes, food enzymes, and animal feed enzymes. These enzymes provide specialized roles in a variety of sectors. In the food industry, 64 enzymes are used for technical purposes, 57 are used in feeds, and 24 are employed in three distinct industrial fields (Seerat Gupta, 2023). Food enzymes are applicable in various industrial sectors such as food and beverage processing, including baking, dairy, beer, wine, fruit, and vegetable juice production and baking (Mandake *et al*., 2020). Animal feed enzymes, the third group, are used in the animal feed industrial sector. Biocatalysts have gained popularity in organic synthesis due to their high quality, greater efficiency, and increased safety (Winkler *et al*., 2021). In this section, we depict the use of industrial enzymes in many industrial areas (Table 1).

Table 1. Application of industrial enzyme.

Uses in industry	Application	Producing organism	Reference
Baking industry			
Glucose oxidase	Dough strengthening	*Aspergillus niger*, *Penicillium chrysogenum*, *Penicillium glaucum*	Wong *et al*., 2008; Khatami *et al*., 2022
Amylase	Flour adjustment, bread softness	*Aspergillus oryzae*, *Bacillus* sp BCC 01-50, *Bacillus licheniformis*	Asgher *et al*., 2007; Dey and Banerjee, 2012; Porfirif *et al*., 2016
Acid protease	Improve the rheological properties of wheat gluten	*Aspergillus usami*	Deng *et al*., 2016
Lipase	Dough stability and conditioning	*Aspergillus niger*, *Penicillium camemberti*	Cong *et al*., 2019
Xylanase	Dough conditioning	*Aspergillus japonicus*, *Penicillium occitanis* Pol6, *Pediococcus acidilactici* GC25	Driss *et al*., 2012; Adiguzel *et al*., 2019
Dairy industry			
Lactase	Lactose-reduced milk and whey products	*Escherichia coli*, *Kluyveromyces lactis*, *Kluyveromyces fragilis*	Wellenbeck *et al*., 2017
Lipase	Faster cheese ripening, flavor customized cheese	*Aspergillus niger*, *A. oryzae*, *Yarrowia lipolytica*, *Rhizopus homothallicus*	Velasco-Lozano *et al*., 2012
Protease	Milk-clotting	*Aspergillus oryzae*	Mamo *et al*., 2020
Transglutaminase	Protein cross linking	*Streptomyces* sp. *Bacillus subtilis*, *B. spherules*	Ceresino *et al*., 2018
Beverage industry			
α -Amylase	Starch hydrolysis	*Bacillus subtilis*, *Aspergillus*	Konsoula and Liakopoulou-Kyriakides, 2007
Esterases	Catalase is the hydrolysis of esters into alcohol and acid	*Lactobacillus farciminis*, *L. fermentum*, *Bacillus licheniformis*	Alvarez-Macarie and Baratti, 2000; Xu *et al*., 2017
Cellulase	Fruit liquefaction	*Aspergillus niger*, *Trichoderma atroviride*, *Trichoderma reesei*	Bhat, 2000
Pectinase	De-pectinization	*Aspergillus oryzae*, *Penicillium funiculosum*, *Aspergillus niger* MTCC, *Bacillus subtilis* ABDR01	Guerrero *et al*., 2015; Oumer, 2017
Protease	Restrict haze formation	*Aspergillus niger*, *Penicillium citrinum*, *Rhizopus stolonifera*	Xiao *et al*., 2015
Glucose oxidase	Oxygen removal from beer	*Aspergillus niger*, *Aspergillus oryzae*, *Cladosporium neopsychrotolerans*	Ge *et al*., 2020 Kornecki *et al*., 2020

Table 1. Contd.

Uses in industry	Application	Producing organism	Reference
Naringinase	Used for making food additives like sweeteners to improve the taste of food	*Aspergillus niger*, *Rhizopus nigricans*, *Cryptococcus albidus*	Borzova *et al*., 2018; Patil *et al*., 2019
Animal feed industry			
β-glucanase	Digestive aid	*Aspergillus niger*	Singh *et al*., 2016
Xylanase	Enhanced digestibility of starch	*Aspergillus* sp., *Bacillus* sp. *Clostridium acetobutylicum*	Collins *et al*., 2005
Phytase	Hydrolyze phytic acid to release phosphorous	*Thermomyces lanuginosus*, *Aspergillus niger*, *Bacillus subtilis*	Berikten and Kivanc, 2014; Ciofalo *et al*., 2003
Amylase		*Thermomyces lanuginosus*	Jensen *et al*., 2002
Pulp and paper industry			
Cellulase	Deinking, drainage improvement	*Bacillus* sp., *Aspergillus niger*, *Bacillus licheniformis*	Yadav *et al*., 2020
Lipase	Pitch control	*Thermomyces lanuginosus*	Šibalić *et al*., 2020
Protease	Biofilm removal	*Bacillus subtilis*, *Bacillus licheniformis*	Gurung *et al*., 2013
Detergent industry			
Cutinase	Triglyceride removal	*Fusarium solani f. pisi*	Chen *et al*., 2013
Amylase	Carbohydrate stain removal	*Aspergillus* sp., *Bacillus subtilis*	Mitidieri *et al*., 2006
Serine protease	Enhance washing efficiency and remove proteinaceous materials from stains	*Flavobacterium balustinum*	Thapa *et al*., 2019
Alkaline protease	Enhance washing efficiency and remove proteinaceous materials from stains	*Stenotrophomonas maltophilia*	Kuddus and Ramteke, 2009
Leather industry			
Amylase	Fiber splitting	*Bacillus licheniformis*, *B. stearothermophilus*, *B. amyloliquefacien*	Zambare, 2011
Lipase	Degreasing	*Bacillus* sp., *Pseudomonas aeruginosa*	Prasad and Manjunath, 2011
Alkaline protease	Dehairing, bating	*Alcaligenes faecalis*	Rao *et al*., 1998
Neutral Protease	Dehairing, soaking	*Aspergillus niger*, *A. flavus*, *Bacillus subtilis*	Rao *et al*., 1998
Cosmetics industry			
Endoglycosidase	Teeth and gum tissue care	*Mucor hiemalis*	Gupta *et al*., 2019
Laccase	Hair dye	*Bacillus subtilis*, *Trametes versicolor*	Gianfreda *et al*., 1999
Protease	Removal of dead skin	*Aspergillus niger*, *A. flavus*, *Bacillus subtilis*	Rao *et al*., 1998
Superoxide dismutase	Free radical scavenging, skin care	*Corynebacterium glutamicum*, *Lactobacillus plantarum*	Singh *et al*., 2016
Waste management			
Amyloglucosidase	Starch hydrolysis for bioremediation	*Aspergillus niger*	Djekrif-Dakhmouche *et al*., 2006
Oxygenase	Degradation of halogenated contaminants	*Pseudomonas* sp., *Rhodococcus* sp.	Arora *et al*., 2009
Amylase	Bioremediation of vegetable wastes	*B. licheniformis*, *Aspergillus* sp.	Karigar and Rao, 2011
Laccase	Degradation of waste containing olefin unit, polyurethane, and phenolic compounds	*Trametes versicolor*	Gianfreda *et al*., 1999

Table 1. Contd.

Uses in industry	Application	Producing organism	Reference
Textile industry			
Catalase	Bleach termination	*Aspergillus niger*	Fiedurek and Gromada, 2000
Ligninase	Wool finishing	*Trametes versicolor*, *Phlebia radiate*	Mojsov, 2011
Pectate lyase	Bio scouring	*Bacillus* sp., *Pseudomonas* sp.	Hugouvieux-Cotte-Pattat *et al*., 2014
Protease	Removal of wool fiber scales, degumming of silk	*Bacillus subtilis*	Pant *et al*., 2015
Cellulase	Cotton softening, denim finishing	*Aspergillus niger*, *Penicillium funiculosum*	Vandamme *et al*., 1998

4. Global and Bangladesh industrial enzymes market

The 21st century has seen significant growth in industrial production, leading to the creation of employment opportunities, increased income, and improved living conditions. Numerous factors, including research and development initiatives, environmental concerns, the food and beverage industry's need for protease and carbohydrates, the fast pace of industrialization, developments in the nutraceutical industry, and the growing demand for bioethanol, all have an impact on the market. With a predicted Compound Annual Growth Rate (CAGR) of 6.6%, the market is predicted to keep growing, rising from USD 7.4 billion in 2023 to USD 10.2 billion by 2028 (Markets and Markets, 2023). The fastest-growing market for industrial enzymes is the food and beverage sector, which is being driven by the rising worldwide population and spending power. Based on IMARC Group's forecast, the global food enzymes market is expected to grow at a compound annual growth rate (CAGR) of 6.9% from 2023 to 2028, from $3.4 billion in 2022 to $5.1 billion (IMARC Food Enzymes Market, 2022). The global industrial enzymes market is primarily dominated by North American countries, accounting for over 30%. The US is ranked first because of its revenue share in the production of beverages and biofuels. The growing demand for craft beer is likely responsible for the market's growth.

Bangladesh exported a total value of $911 enzyme in the year 2021, putting it in the position as the 119th-largest enzyme exporter worldwide. The United Arab Emirates, China, Sri Lanka, South Korea, and Turkey are Bangladesh's top export markets for enzymes. Bangladesh's Enzymes had significant growth in their export markets from 2020 to 2021. Bangladesh ranked as the 34th largest importer of enzymes worldwide in the same year, with an import value of $47.4 million. Bangladesh mainly imports enzymes from Turkey, Malaysia, China, Singapore, and Sri Lanka. The fastest-growing import markets between 2020 and 2021 were China ($2.3M), Spain ($1.07M), and Italy ($1.02M) (Intelligence, 2022) and (OEC, 2023).

Bangladesh still depends on imports since it lacks a specialized industrial enzyme production industry, but the global market for industrial enzymes is flourishing day by day and the most promising areas are the food and beverage industry.

5. Enzyme production technologies

Enzyme manufacturing technologies can make a significant contribution to environmental protection. This can occur during the manufacturing, use, or disposal of enzymes by conserving resources, lowering global greenhouse gas (GHG) emissions, encouraging energy-efficient operations and the use of renewable energy, eliminating harmful agents, reducing waste, and conserving water. Hence, it can be argued that the utilization of enzyme-derived products holds the promise of yielding positive outcomes for both the natural ecosystem and the overall well-being of individuals (Molina-Espeja *et al*., 2023).

The main producers of enzymes are animals, microbes, and plants. Sixty percent of industrial enzymes are produced by fungi, with the remaining forty percent coming from higher animals, plants, yeast, Streptomyces, and bacteria. Significant advances in biotechnology, particularly in the areas of directed evolution and protein engineering, have aided the production of new enzymes (Kaur and Gill, 2019).

Food enzymes can be derived through two main methods: microbial (MO) fermentation or extraction from zoological and animal sources. Initially, Enzymes derived from plants and animals were considered superior to enzymes made by microbial fermentation due to the belief that they contained fewer contaminants. However, the advantages of microbial biomass (MB) fermentations, such as their affordability, technological viability, and ethical advantages (particularly in comparison to animal sources)—have grown more and more evident (Zhang *et al*., 2019).

Microorganisms can produce enzymes via a variety of fermentation processes, including submerged fermentation (SmF) and solid-state fermentation (Kaur and Gill, 2019).

5.1. Methods of microbial fermentation

5.1.1. Submerged fermentation (SmF)

Submerged fermentation (SmF) is a technique for growing specialized bacterial and fungal strains in a nutrient-enriched liquid medium, producing enzymes for industrial use. Large-scale fermenters, some with capacities of up to 1,000 cubic meters, are employed. These microbes secrete enzymes into the liquid, catalyzing the breakdown of carbon and nitrogen molecules. Adequate water supply and high oxygen levels are crucial for this process, which employs stirring mechanisms such as stirrers and impellers. Various factors, including temperature, pH, agitation, and foam control, impact the process. Four SmF variations exist batch, fed-batch, perfusion, and continuous, depending on operational modes in bioprocessing (Al-Maqtari *et al.*, 2019; Deckers *et al.*, 2020).

5.1.2. Solid state fermentation (SSF)

Solid-state fermentation is a bioprocess technique through wherein certain microorganisms (bacteria, fungi, and yeasts) are cultivated on a moist, solid, non-soluble organic material that serves as both a support and nutrient source for the growth of the microorganisms, in the absence or near absence of free-flowing water. This process occurs in an environment with limited or no free-flowing water. The solid-state fermentation (SSF) technique, employed for industrial enzyme production, utilizes nutrient-rich waste products such as bran, bagasse, and paper pulp as substrates for microorganisms. These bacteria gradually and continuously consume these substrates. The advantages of this technology comprise its ease of handling, enhanced recovery of product concentration, and reduced creation of effluent. These factors contribute to its potential as a viable approach for sustained substrate supply (Toldra and Kim, 2016). Several enzymes derived from solid-state fermentation include the following examples: cellulases, α-amylases, proteases, lipases, phytases, laccases, xylanases, xylosidases, chitin deacetylase and invertase (Yafetto, 2022).
The manufacturing process of industrial enzymes typically follows a fundamental methodology. The methodology can be summarized as follows:

- Selection of an enzyme
- Production strain selection
- It is possible to create overproducing strains through recombinant DNA technology.
- Conditions for medium optimization and control of the parameters
- Optimization of product recovery process and
- In the final stage, the product (enzyme) is formulated to be long lasting and have a longer shelf life (Nandy, 2016) (Figure 1).

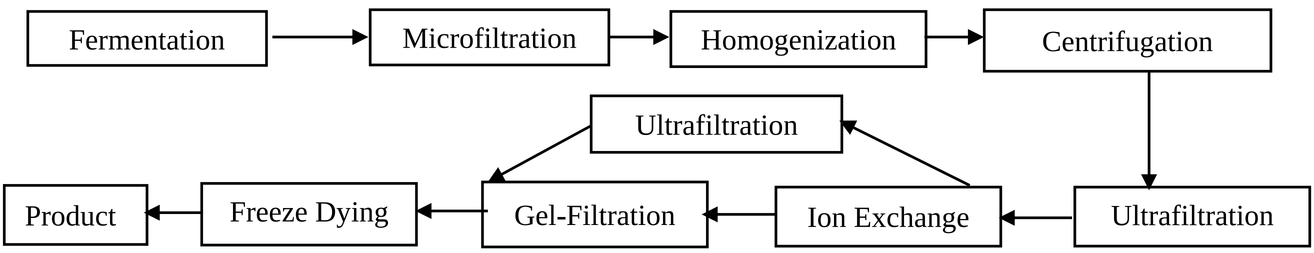

Figure 1. A schematic representation in the form of a block diagram is used to visually depict the process of enzyme manufacturing (Nandy, 2016).

5.2. Recombinant DNA technology

Enzyme augmentation involves altering the genetic composition of an organism or the enzyme itself. Various strategies have been employed to produce improved recombinant enzymes. The choice of a specific strategy depends on having a thorough grasp of the structure, function, and sequence of enzymes as well as the modifications required to get the desired results.

5.2.1. Rational design

Rational design includes the modification of certain DNA sequences that control amino acids linked to more effective focused action. It is crucial to comprehend the three-dimensional structure and molecular functions of proteins. Site-directed mutagenesis frequently involves the substitution of particular amino acids with others to achieve the desired functionality (Sanchez and Demain, 2017).

5.2.2. Directed evolution

The process of directed evolution consists of two distinct stages.

5.2.2.1. Generating genetic diversity

The introduction of initial genetic variation through several processes including UV radiation, chemical mutagenesis, or error-prone PCR facilitates the creation of genetic diversity. By creating enzyme variations with a diverse variety of genetic makeup, this approach mimics the process of natural evolution.

5.2.2.2. Screening and selection

The next step is to use screening and selection procedures to assess the modified enzymes for the desired properties. This phenomenon frequently shows up on various substrates, such as agar plates. Enzymes that exhibit the required characteristics are chosen. Unlike rational design, however, this specific technique does not require knowledge of the structure and function of enzyme (Zhang *et al*., 2019).

5.2.3. Semi-rational design

Combining guided evolution methods with rational design concepts is the idea behind semi-rational design. This means that while you may have a thorough grasp of the structural and functional properties of the enzyme, you may lack particular knowledge of the modifications that are required to produce the intended outcomes. Targeted mutations are added to specific amino acids in a relevant region during the first stage. Then, an evaluation and screening process based on directed evolution principles is applied to find variants of the enzyme that meet the required criteria (Trono, 2019).

6. Research and development

In Bangladesh, several research organizations and university research laboratories conducted several research works to produce enzymes from microorganisms and plant sources. Recently, a project to analyze the proteolytic enzyme produced by Koji Mold was initiated in 2022–2023 by the Centre for Advanced Research in Sciences (CARS). The 2021–2022 Bangladesh Council of Scientific and Industrial Research (BCSIR) annual report showcased several projects undertaken by its researchers. One of these projects focused on the isolation and identification of indigenous fungi for the bioremediation of dye effluents. The researchers identified the enzymes responsible for dye degradation activity using biotechnological techniques. Another effort attempted to increase the production of protease for use in a variety of industries. BCSIR also conducted research on the improvement of xylanase production by a newly isolated xylanolytic bacteria using mutation and gene cloning. Another scientist also headed a project on the extraction of alkaline protease enzyme and its industrial application in the tannery industry. Urea-induced urease activity was studied at the University of Rajshahi's Department of Biochemistry and Molecular Biology, notably the Laboratory of Protein and Enzyme Research, and its possible role in enhancing the fertilization of Mango flowers. From 2013 to 2019, the National Institute of Biotechnology undertook research on the manufacture and development of eco-friendly enzymes derived from microorganisms for use in the textile industry (NIB, 2023).

7. Agricultural resources and biodiversity

The food and agriculture industry are growing rapidly. However, the process of industrialization has led to harmful effects on the environment. Biomass is produced annually, rice husk, rice straw, jute sticks, and sugarcane bagasse are examples of agricultural waste that contributes significantly to Bangladesh's biomass energy supply (Bharathiraja *et al*., 2017). It is critical to turn these wastes into valuable industrial and commercial items efficiently and cost-effectively to reduce their negative adverse effect on the environment (Wang *et al*., 2016).

Agricultural waste, such as corn cobs, sawdust, rice hulls, and groundnut shells, can be utilized for multiple industrial applications owing to its richness in bioactive chemicals, including the production of antibiotics (Kashif and Shahid, 2022). Agricultural waste has been used effectively for carbon and nitrogen in procedures such as antimicrobial fermentation throughout the first half of the 20th century (Ravindran *et al*., 2018). In order to effectively address the problem of waste accumulation, a link between waste streams and agro-based sectors needs to be established. Production of everyday items such as food, feed, paper, textiles, chemicals, and medications necessitates significant resource consumption and produces waste, which has an adverse effect on the environment and people's quality of life (Jiuyang Lin, 2023). Untreated effluents discharged into aquatic ecosystems by the textile industry often result in serious environmental damage (Lellis *et al*., 2019).

Industries on a global scale are actively pursuing alternative technologies to address the growing demand for goods and services, while simultaneously minimizing resource use and mitigating environmental repercussions. The food industry, part of the agro-industry, significantly contributes to waste production, leading to economic losses, climate change, and environmental pollution (Singh *et al*., 2021). The industrialization of biology has the potential to yield significant benefits at both the global and national levels. It can spur innovation and sustainable economic growth, while also helping to address several of the most pressing obstacles of our time, such as providing inexpensive clean energy, enabling persisting production processes, and creating new jobs and skills for future generations (NRC, 2015).

Enzyme production could be made more economically by using biological waste as a medium for the growth of microorganisms. The capacity of enzyme preparations sourced from fungi and bacteria to break down biomass is somewhat limited. Despite the limitations on their effectiveness, enzymes have attracted significant industrial use in the areas of food modification, biofuel production, pharmaceutical and biological research, and waste conversion.

8. Environmental concern

Enzyme catalysis has proven to be advantageous for various industries like pharmaceuticals, food and beverage, detergent, and biofuel. However, other sectors like natural gas conversion and fine chemical manufacture have recently begun evaluating its utilization. Employing enzymes as catalysts in large-scale chemical manufacturing offers numerous advantages. Enzymes are excellent catalysts due to their ability to work under mild reaction conditions, excellent selectivity towards products, and minimal impact on the environment. Therefore, they have been utilized to optimize chemical synthesis pathways and enhance the cost-effectiveness of chemical processes (Chapman *et al*., 2018).

Industrialization and rapid urbanization have all accelerated environmental degradation since 1940s, by releasing dangerous pollutants in the environment (Ali *et al*., 2019). The most prevalent contaminants in the environment are pesticides, polycyclic aromatic hydrocarbons (PAHs), heavy metals, dyes, and plastics. These compounds' propensity to cause cancer, incapacity to break down organically, and persistent presence in the environment make them especially dangerous and destroy our ecosystem. They are persistent in their impacts and are the cause of harmful illnesses that affect humans, animals, and plants in these settings (Vardhan *et al*., 2019).

Bioremediation uses microorganisms or their enzymes to remove toxic pollutants from the environment. Bacterial and fungal enzymes can convert pollutants into non-toxic forms through catalytic reactions. The process is safe, efficient, and economically viable, using enzymes like oxidoreductases, oxygenases, hydrolases, peroxidases, phosphodiesterases, and lipases to break down harmful contaminants (Sharma *et al*., 2018). Enzymes are ideal for environmental applications due to their variety, selectivity, and biodegradability. However, their industrial use is limited by the high cost of purified enzymes. Genetic engineering can overcome this challenge by producing enzymes that are more specific and cost-effective, reducing the need for traditional manufacturing methods (Al-Maqdi *et al*., 2021).

The textile business is resource-intensive since it relies on raw cotton for yarn and fabric. Extensive operations such as scouring, bleaching, polishing, and dyeing harm the environment. Pectate lyase is an enzymatic catalyst that facilitates the degradation of pectin, a complex polysaccharide found in plant cell walls. This enzyme is used in the scouring procedure to help in the efficient removal of impurities, hence reducing energy and chemical requirements Knitted fabrics and yarns are bleached with hydrogen peroxide before dying, and any remaining hydrogen peroxide must be removed to prevent interference with subsequent dyeing steps (Roy Choudhury, 2014). Catalases possess the ability to enzymatically degrade excess hydrogen peroxide at reduced temperatures, hence rendering the process more cost-effective and ecologically sustainable (Haddar *et al*., 2023). Enzymes offer industrial operations a safer, more effective, and biodegradable substitute. By minimizing waste production, consuming less energy, and reducing the need for dangerous chemicals, they assist the industry in meeting environmental goals (Table 2).

Table 2. Applications of enzyme for environmental sustainability in various industries.

Uses of enzymes in industry	Name of the enzymes	Environmental benefit	Reference
Textile industry	Pectate lyase	Used in the scouring process to help remove impurities from textiles more effectively.	Wu *et al*., 2020
	Catalase	Used in textile processing to hydrolyze hydrogen peroxide into water and oxygen at lower temperatures, conserving energy, heat, and water.	Nielsen *et al*., 2009
Food and beverage industry	Pectinase	Used to reduce carbon dioxide emissions and increase juice quality in the manufacture of apple juice.	Dunn, 2012
Detergent industry	Enzymes	Used as detergent additives to successfully remove stains at lower temperatures, minimizing the need for higher water temperatures and energy usage.	Sekhon and Sangha, 2004
Pharmaceutical industry	Phenylalanine ammonia-lyase, Lipase, Penicillin amidase, D-amino acid oxidase, and glutaryl 7-ACA acylase	Enzymes are employed in pharmaceutical manufacturing to generate environmentally friendly procedures that reduce energy and chemical usage while also minimizing hazardous waste formation.	Pollard and Woodley, 2007
Animal feed processing industry	Xylan	A kind of dietary fiber included in cereals that can be broken down by enzyme activities so that it may be absorbed by animals with a monogastric stomach. This helps to preserve feed and lowers emissions from the treatment of manure.	Skals *et al*., 2008

9. Government support and incentives

The development and advancement of numerous governmental and commercial organizations should be included in the pharmaceutical sector to facilitate the manufacturing of pharmaceuticals and medical items. Bangladesh's pharmaceutical industry is now seeing rapid growth, with a CAGR of 15.6% over the next five years. Several factors contribute to the expansion: rising Gross National Income (GNI) per capita; population growth; changes in health patterns; modifications to lifestyle choices; and urbanization. Exports have contributed significantly more than they did in the previous fiscal year. The pharmaceutical industry can enter foreign markets, especially in developing nations where more than half of the world's drug consumption takes place. Utilizing technology like artificial (Faisal, 2019). Bangladesh's government has incentivized the pharmaceutical industry to attract local and international investors. These measures include encouraging foreign companies to partner with local companies, easing regulations, and providing access to US exporters, and implementing tax breaks. The government has also reduced customs taxes, approved land allotment, and proposed an economic incentive of 10%. The pharmaceutical sector has been a prominent area of emphasis in the export strategy since 2006 (Mohiuddin, 2019).

Bangladesh has potential in biotechnology, but political barriers, corruption, and a lack of commitment prevent it from moving further. Although there are some encouraging projects, the nation is not using the most advanced gene transfer methods. The government provides incentives including tax cuts, lower import duties, and export subsidies to entice investment. Reduced income taxes are available to newly established biotech businesses between July 1, 2019, and June 30, 2024. Nonetheless, more committed work is required to fully achieve biotechnology's potential in Bangladesh (BIDA, 2019).

In addition, the application of agricultural waste as a substitute biomass source has raised significant concerns for the environment and renewable energy to satisfy demand worldwide. In Bangladesh, agricultural waste is mainly used for cooking purposes, accounting for 92% of overall primary energy consumption and about 60% of total energy consumption (Uddin *et al*., 2019).

10. Challenges and considerations

The pharmaceutical sector in Bangladesh is highly dependent on imported raw materials, which drives up prices and lowers its competitiveness. Manufacturing of raw materials must be localized if exports and the economy are to grow. The government has made the sector a top priority and has set up Bangladesh to export APIs successfully. A recognized manufacturing facility, established production techniques, strict quality control, and skilled personnel are required to sell pharmaceutical products from Bangladesh in regulated markets. To boost exports, Bangladesh ought to construct a bioequivalence testing center. The protection of pharmaceutical patents, funding gaps in research, fake medications, and quality control problems all pose problems for the sector. Cost-cutting and self-sufficiency depend on local production (Mohiuddin, 2019).

In the past, the field of medical biotechnology lacked adequate facilities. However, today there has been a significant increase in healthcare and diagnostic services. Several organizations, like the International Centre for Diarrhoeal Disease Research in Bangladesh (ICDDR, B), Bangladesh Institute of Research in Diabetic, Endocrine and Metabolic Disorders (BIRDEM), Institute of Public Health (IPH), and the Institute of Epidemiology, Disease Control and Research (IEDCR), are among the most prominent. To progress biotechnology research in the nation, specialized facilities and equipment are also required, in addition to highly qualified personnel (Islam, 2016).

Bangladesh's rapidly expanding population is making food security an increasingly pressing concern. The difficulties associated with meeting demand for rice are exacerbated by supply-side problems (Hossain, 2023).

Bangladesh's textile industry suffers difficulties as a result of antiquated machinery and technology, which raises production costs and reduces the country's competitiveness in the area. Pesticide cartels and poor cotton quality are to blame for the industry's expansion being further impeded (Niloy, 2023).

Agricultural-based biomass production for biofuel generation on a large scale may give rise to concerns regarding economic, social, and environmental sustainability (Gan *et al*., 2019). Furthermore, the "food vs. fuel" issue emphasizes the importance of long-term biofuel feedstock availability to meet rising food prices connected with biofuel production (Luthra *et al*., 2015).

Numerous enzymes that are vital to the country's industries are being studied, such as enzymes that break down lignocellulose, enzymes that are amylolytic, and enzymes used in biotechnology. The emphasis is on industrial enzymes that are very prolific and can function effectively in harsh environments. The field of industrial enzymes is making major strides because of this research (BIOTEC, 2023).

Globally, the enzyme market is expanding as a result of growing investments in biotechnology and research, especially in the creation of innovative drugs and diagnostics. Increased demand, significant research efforts, and solid funding are anticipated to propel the medical pharmaceutical sector. The demand for enzymes is being driven by a variety of industries, including molecular biology, biofuels, paper processing, rubber processing, biological detergents, and contact lens cleansers. The market for enzymes is expanding as a result of various factors, including rising dietary requirements, population expansion, and consumer awareness of food quality (Madaan, 2020).

11. Future outlook

Bangladesh lacks the infrastructure necessary for the development of industrial enzymes while being a developing nation. Government involvement in this industry is necessary to support regional production of enzymes, satisfy home demand, and even export enzymes overseas. Cooperation with nearby nations that currently produce enzymes, such as China, Japan, and India, could be taken into consideration. Notably, China intends to develop an enzyme industry in Bangladesh in the future; however, one of the obstacles is the need for a steady supply of electricity for the synthesis of enzymes. Production in Bangladesh is anticipated to start in around five years (Yee, 2018).

12. Conclusions

Enzymes are biocatalysts that offer economic and environmental benefits across various industries. The demand for enzymes is anticipated to increase substantially globally, providing an opportunity for manufacturers to develop new products and utilize technological advances such as structural biology, screening techniques, bioinformatics tools, and modern biotechnology. Bangladesh's industrial sector is experiencing substantial growth. Our study provides a detailed analysis of agro-industrial waste and its conversion into valuable products, market dimensions, financial gains, expansion patterns, and trends for different types of enzymes, emphasizing their utilization trends. The industrial enzyme market in Bangladesh has the potential to expand due to rising demand, a highly skilled labor force, and low labor costs. The government has demonstrated support for the sector through tax reductions and incentives for enzyme manufacturers. However, the sector faces challenges such as the lack of awareness of enzyme benefits, the high-cost of imported enzymes, and limited accessibility of domestic research and development. With adequate support from the government and industry partners, the large-scale industrial enzyme production sector should be developed which can make a substantial contribution to the economic development and advancement of the nation.

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Data availability
The dataset that arose and was used in the current study is available from the corresponding author on reasonable request.

Conflict of interest
None to declare.

Authors' contribution
Imam Hossain, Israt Jahan Mitu, Md. Rakibul Hasan, and Sumita Rani Saha conducted the studies, including data collection, data curation, and data analysis, and participated in drafting the manuscript. Imam Hossain critically reviewed and contributed to manuscript drafting. Sumita Rani Saha and Imam Hossain were responsible for visualizing the tables. Sumita Rani Saha developed the hypothesis, supervised the entire project, and assisted in manuscript preparation, critical review, and editing. All authors reviewed and approved the final manuscript.

References
Adiguzel G, O Faiz, M Sisecioglu, B Sari, O Baltaci, S Akbulut, B Genc and A Adiguzel, 2019. A novel endo-β-1, 4-xylanase from *Pediococcus acidilactici* GC25; purification, characterization and application in clarification of fruit juices. Int. J. Biol. Macromol., 129: 571-578.

Al-Maqdi KA, N Elmerhi, K Athamneh, M Bilal, A Alzamly, SS Ashraf and I Shah, 2021. Challenges and recent advances in enzyme-mediated wastewater remediation-a review. Nano Materiol., 11: 3124.

Al-Maqtari QA, A Waleed and AA Mahdi, 2019. Microbial enzymes produced by fermentation and their applications in the food industry-A review. Int. J. Agri. Inno. Res., 8: 2319-1473.

Alvarez-Macarie E and J Baratti, 2000. Short chain flavour ester synthesis by a new esterase from *Bacillus licheniformis*. J. Mol. Catal. B Enzym., 10: 377-383.

Ali H, E Khan and I Ilahi, 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J. Chem., 2019:1-14

Arora PK, M Kumar, A Chauhan, GP Raghava and RK Jain, 2009. OxDBase: a database of oxygenases involved in biodegradation. BMC. Res. Notes., 2: 1-8.

Asgher M, MJ Asad, S Rahman and R Legge, 2007. A thermostable α-amylase from a moderately thermophilic *Bacillus subtilis* strain for starch processing. J. Food Eng., 79: 950-955.

ADB (Asian Development Bank), 2023. Bangladesh economy to grow moderately amid global economic slowdown. Available: https://www.adb.org/news/bangladesh-economy-grow-moderately-amid-global-economic-slowdown.

BIDA (Bangladesh Investment Development Authority), 2019. General incentives. Available: https://bida.gov.bd/incentives.

Berikten D and M Kivanc, 2014. Optimization of solid-state fermentation for phytase production by *Thermomyces lanuginosus* using response surface methodology. Prep. Biochem. Biotechnol., 44: 834-848.

Bharathiraja S, J Suriya, M Krishnan, P Manivasagan and SK Kim, 2017. Production of enzymes from agricultural wastes and their potential industrial applications. Adv. Food Nutr. Res., 80:125-148.

Bhat M, 2000. Cellulases and related enzymes in biotechnology. Biotechnol. Adv., 18: 355-383.

Borzova N, O Gudzenko and L Varbanets, 2018. Purification and characterization of a naringinase from *Cryptococcus albidus*. Appl. Biochem. Biotechnol.,184: 953-969.

Carolin CF, PS Kumar, GJ Joshiba, P Madhesh and R Ramamurthy, 2021. Sustainable strategy for the enhancement of hazardous aromatic amine degradation using lipopeptide biosurfactant isolated from *Brevibacterium casei*. J. Hazard Mater., 408: 124943.

Ceresino EB, de RR Melo, R Kuktaite, MS Hedenqvist, TD Zucchi, E Johansson and HH Sato, 2018. Transglutaminase from newly isolated *Streptomyces sp*. CBMAI 1617: Production optimization, characterization and evaluation in wheat protein and dough systems. Food Chem., 241: 403-410.

Chapman J, AE Ismail and CZ Dinu, 2018. Industrial applications of enzymes: Recent advances, techniques, and outlooks. Catalysts., 8: 238.

Chen S, L Su, J Chen and J Wu, 2013. Cutinase: characteristics, preparation, and application. Biotechnol. Adv., 31: 1754-1767.

Ciofalo V, N Barton, K Kretz, J Baird, M Cook and D Shanahan, 2003. Safety evaluation of a phytase, expressed in *Schizosaccharomyces pombe*, intended for use in animal feed. Regul. Toxicol. Pharmacol., 37: 286-292.

Collins T, C Gerday and G Feller, 2005. Xylanases, xylanase families and extremophilic xylanases. FEMS Microbiol. Rev., 29: 3-23.

Cong S, K Tian, X Zhang, F Lu, S Singh, B Prior and ZX Wang, 2019. Synthesis of flavor esters by a novel lipase from *Aspergillus niger* in a soybean-solvent system. 3 Biotech., 9: 1-7.

Deckers M, D Deforce, MA Fraiture and NH Roosens, 2020. Genetically modified micro-organisms for industrial food enzyme production: an overview. Foods., 9: 326.

Deng L, Z Wang, S Yang, J Song, F Que, H Zhang and F Feng, 2016. Improvement of functional properties of wheat gluten using acid protease from *Aspergillus usamii*. Plos One, 11: e0160101.

Dey T and R Banerjee, 2012. Hyperactive α-amylase production by *Aspergillus oryzae* IFO 30103 in a new bioreactor. Lett. Appl. Microbiol., 54: 102-107.

Djekrif-Dakhmouche S, Z Gheribi-Aoulmi, Z Meraihi and L Bennamoun, 2006. Application of a statistical design to the optimization of culture medium for α-amylase production by *Aspergillus niger* ATCC 16404 grown on orange waste powder. J. Food. Eng., 73: 190-197.

Driss D, F Bhiri, M Siela, R Ghorbel and SE Chaabouni, 2012. Purification and properties of a thermostable xylanase GH 11 from *Penicillium occitanis* Pol6. Appl. Biochem. Biotechnol., 168: 851-863.

Dunn PJ, 2012. The importance of green chemistry in process research and development. Chem. Soc. Rev., 41: 1452-1461.

Faisal M, 2019. Pharmaceutical industry of Bangladesh: A multi-billion dollar industry. Eastern Bank Limited Securities Ltd, Dhaka. pp. 40.

Farooq MA, S Ali, A Hassan, HM Tahir, S Mumtaz and S Mumtaz, 2021. Biosynthesis and industrial applications of α-amylase: A review. Arch. Microbiol., 203: 1281-1292.

Fiedurek J and A Gromada, 2000. Production of catalase and glucose oxidase by *Aspergillus niger* using unconventional oxygenation of culture. J. Appl. Microbiol., 89: 85-89.

Gan J, I Stupak and C Smith, 2019. Integrating policy, market, and technology for sustainability governance of agriculture-based biofuel and bioeconomic development in the US. Energ. Sustain. Soc., 9: 1-25.

Ge J, X Jiang, W Liu, Y Wang, H Huang, Y Bai, X Su, B Yao and H Luo, 2020. Characterization, stability improvement, and bread baking applications of a novel cold-adapted glucose oxidase from *Cladosporium neopsychrotolerans* SL16. Food Chem., 310: 125970.

Gianfreda L, F Xu and JM Bollag, 1999. Laccases: a useful group of oxidoreductive enzymes. J. Bioremed., 3: 1-26.

Girelli AM, ML Astolfi and FR Scuto, 2020. Agro-industrial wastes as potential carriers for enzyme immobilization: A review. Chemosphere., 244: 125368.

Guerrero C, C Vera, E Araya, R Conejeros and A Illanes, 2015. Repeated-batch operation for the synthesis of lactulose with β-galactosidase immobilized by aggregation and crosslinking. Bioresour. Technol., 190: 122-131.

Gupta PL, M Rajput, T Oza, U Trivedi and G Sanghvi, 2019. Eminence of microbial products in cosmetic industry. Nat. Prod. Bioprospect., 9: 267-278.

Gurung N, S Ray, S Bose and V Rai, 2013. A broader view: microbial enzymes and their relevance in industries, medicine, and beyond. Biomed. Res. Int., 2013: 329121.

Haddar W, S Adeel, M Salman, A Ghaffar, M Naseer, M Usama and M Benticha, 2023. Ecological applications of enzymes in plants based textile dyeing. Intechopen., 2023: 108603.

Hossain DM, 2023. Food Security in Bangladesh: Achievement and challenges. Available: https://www.thedailystar.net/news/achievement-and-challenges.

Hugouvieux-Cotte-Pattat N, G Condemine and VE Shevchik, 2014. Bacterial pectate lyases, structural and functional diversity. Environ. Microbiol. Rep., 6: 427-440.

IMARC Food Enzymes Market, 2022. Food enzymes market report by type (carbohydrase, protease, lipase, and others), source (microorganisms, plants, animals), formulation (powder, liquid, and others), application (beverages, processed foods, dairy products, bakery products, confectionary products, and others), and region 2023-2028. Available: https://www.imarcgroup.com/food-enzymes-market.

Intelligence M, 2022. Industrial enzymes market size and share analysis - growth trends and forecasts (2023-2028). Available: https://www.mordorintelligence.com/industry-reports/industrial-enzymes-market.

Islam MSMS, 2016. Potentials of biotechnology. Available: https://www.thedailystar.net/25th-anniversary-special-part-1/potentials-biotechnology-210547.

Jensen B, P Nebelong, J Olsen and M Reeslev, 2002. Enzyme production in continuous cultivation by the thermophilic fungus, Thermomyces lanuginosus. Biotechnol. Lett., 24: 41-45.

Karigar CS and SS Rao, 2011. Role of microbial enzymes in the bioremediation of pollutants: a review. Enzyme Res., 2011:805187.

Kashif A and MK Shahid, 2022. Agricultural wastes as an alternative source for the production of antibiotics: recent developments and future perspectives. In: Advances in agricultural and industrial microbiology. Edited by: Nayak SK, B Baliyarsingh, I Mannazzu, A Singh, BB Mishra, Springer, Singapore, pp.125-136.

Kaur H and PK Gill, 2019. Microbial enzymes in food and beverages processing, in engineering tools in the beverage industry. In: Engineering tools in the beverage industry. Edited by: Grumezescu AM and AM Holban, Woodhead Publishing, pp. 255-282.

Khatami SH, O Vakili, N Ahmadi, FE Soltani, P Mousavi, B Khalvati, A Maleksabet, A Savardashtaki, MT Anganeh and A Movahedpour, 2022. Glucose oxidase: Applications, sources, and recombinant production. Biotechnol. Appl. Biochem., 69: 939-950.

Konsoula Z and M Liakopoulou-Kyriakides, 2007. Co-production of α-amylase and β-galactosidase by Bacillus subtilis in complex organic substrates. Bioresour. Technol., 98: 150-157.

Kornecki JF, D Carballares, PW Tardioli, RC Rodrigues, Á Berenguer-Murcia, AR Alcantara and R Fernandez-Lafuente, 2020. Enzyme production of D-gluconic acid and glucose oxidase: successful tales of cascade reactions. Catal. Sci. Technol., 10: 5740-5771.

Kuddus M and PW Ramteke, 2009. Cold-active extracellular alkaline protease from an alkaliphilic *Stenotrophomonas maltophilia*: production of enzyme and its industrial applications. Can. J. Microbiol., 55: 1294-1301.

Lellis B, CZ Fávaro-Polonio, JA Pamphile and JC Polonio, 2019. Effects of textile dyes on health and the environment and bioremediation potential of living organisms. Biotechnol. Res. Innov., 3: 275-290.

Luthra S, S Kumar, D Garg and A Haleem, 2015. Barriers to renewable/sustainable energy technologies adoption: Indian perspective. Renew. Sustain. Energy. Rev., 41: 762-776.

Mandake MB, U Das, L Phad and S Busamwar, 2020. Application of enzyme immobilization in the food industry. Int. J. Adv. Res. Chem. Sci., 7: 6-10.

Madaan M, 2020. Importance of innovation in industrial enzymes. Available: https://www.linkedin.com/pulse/importance-innovation-industrial-enzymes-munish-madaan?articleId=6660765579961606145.

Madhavan A, K Arun, P Binod, R Sirohi, A Tarafdar, R Reshmy, MK Awasthi and R Sindhu, 2021. Design of novel enzyme biocatalysts for industrial bioprocess: Harnessing the power of protein engineering, high throughput screening and synthetic biology. Bioresour. Technol., 325: 124617.

Mamo J, P Getachew, KM Samuel and F Assefa, 2020. Application of milk-clotting protease from *Aspergillus oryzae* DRDFS13 MN726447 and *Bacillus subtilis* SMDFS 2B MN715837 for Danbo cheese production. J. Food Qual., 2020: 1-12.

Markets and Markets, 2023. Industrial enzymes market by type (carbohydrases, proteases, lipases, polymerases & nucleases), application (food & beverages, bioethanol, feed, detergents, wastewater, soil, and oil treatment), source, formulation and region - global forecast to 2028. Available: https://www.marketsandmarkets.com/PressReleases/industrial-enzymes.asp.

McGovern P, M Jalabadze, S Batiuk, MP Callahan, KE Smith, GR Hall, E Kvavadze, D Maghradze, N Rusishvili and L Bouby, 2017. Early neolithic wine of Georgia in the South Caucasus. Proc. Natl. Acad. Sci. USA, 114: E10309-E10318.

Mitidieri S, AHS Martinelli, A Schrank and MH Vainstein, 2006. Enzymatic detergent formulation containing amylase from *Aspergillus niger*: a comparative study with commercial detergent formulations. Bioresour. Technol., 97: 1217-1224.

Mohiuddin A, 2019. An AZ of Bangladesh pharmaceutical industry. Marketing Research 1: 2.

Mojsov K, 2011. Application of enzymes in the textile industry: A review Primena Na Enzimi Vo Tekstilnata Industrija: Pregled. Int. Cong. Eng. Ecol. Mat. Proc. Ind., 1: 1-17.

Molina-Espeja P, J Sanz-Aparicio, PN Golyshin, A Robles-Martín, V Guallar, F Beltrametti, M Müller, MM Yakimov, J Modregger and van M Logchem, 2023. Enzymes for consumer products to achieve climate neutrality. Oxf. Open Clim. Chan., 3: kgad003.

Nandy S, 2016. Bioprocess technology governs enzyme use and production in industrial biotechnology: an overview. Enz. Eng., 144: 1-5.

BIOTEC (National Center for Genetic Engineering and Biotechnology), 2023. Research and Development. Available: https://www.biotec.or.th/enzymelab/index.php/research-development.

NIB (National Institute of Biotechnology), 2023. Project list. Available: http://www.nib.gov.bd/site/view/projects/-

NRC, 2015. Industrialization of biology: a roadmap to accelerate the advanced manufacturing of chemicals. The National Academies Press, Washington, USA.

Nielsen P, H Kuilderd, W Zhou and X Lu, 2009. Enzyme biotechnology for sustainable textiles. In: Sustainable textiles, Edited by: Blackburn RS, Elsevier, pp. 113-138.

Niloy AC, 2023. A liquid future: Beverage industry of Bangladesh and its prospects. Available: https://www.researchgate.net/publication/368642116.

Nomani S, M Rasel and IK Reedoy, 2022. Industrial development and climate change: a case study of Bangladesh. J. Inno. Appl. Sci., 2: 68-79.

Nunes CS and V Kumar, 2018. Enzymes in human and animal nutrition: principles and perspectives, Academic Press.
OEC, 2023. The best place to explore trade data, Available: https://oec.world/en.
Oumer OJ, 2017. Pectinase: substrate, production and their biotechnological applications. Int. J. Env. Agri. Biotechnol., 2: 1007-1014.
Pant G, A Prakash, J Pavani, S Bera, G Deviram, A Kumar, M Panchpuri and RG Prasuna, 2015. Production, optimization and partial purification of protease from *Bacillus subtilis*. J. Taibah Univ. Sci., 9: 50-55.
Patil SV, SH Koli, BV Mohite, RP Patil, RR Patil, HP Borase and VS Patil, 2019. A novel screening method for potential naringinase-producing microorganisms. Biotechnol. Appl. Biochem., 66: 323-327.
Pollard DJ and JM Woodley, 2007 Biocatalysis for pharmaceutical intermediates: the future is now. Trends. Biotechnol., 25: 66-73.
Porfirif MC, EJ Milatich, BM Farruggia and D Romanini, 2016 Production of alpha-amylase from *Aspergillus oryzae* for several industrial applications in a single step. J. Chromatogr. B Biomed. Appl., 1022: 87-92.
Prasad M and K Manjunath, 2011. Comparative study on biodegradation of lipid-rich wastewater using lipase producing bacterial species. J. Biotechnol., 10: 121-124.
Rao MB, AM Tanksale, MS Ghatge and VV Deshpande, 1998. Molecular and biotechnological aspects of microbial proteases. Microbiol. Mol. Biol. Rev., 62: 597-635.
Raveendran S, B Parameswaran, SB Ummalyma, A Abraham, AK Mathew, A Madhavan, S Rebello and A Pandey, 2018. Applications of microbial enzymes in food industry. Food Technol. Biotechnol., 56: 16.
Ravindran R, SS Hassan, GA Williams and AK Jaiswal, 2018. A review on bioconversion of agro-industrial wastes to industrially important enzymes. Bioeng., 5: 93.
Roy Choudhury A, 2014. Sustainable textile wet processing: Applications of enzymes. In: Roadmap to sustainable textiles and clothing: eco-friendly raw materials, technologies, and processing methods. Edited by: Muthu S, Springer, Singapore, pp. 203-238.
Samanta S, 2022. Structural and catalytical features of different amylases and their potential applications. Jordan J. Biol. Sci., 15: 311-337.
Sanchez S and AL Demain, 2017. Useful microbial enzymes—an introduction. In: Biotechnology of microbial enzymes. Edited by: Brahmachari G, AL Demain, JL Adrio, Elsevier, pp. 1-11.
Seerat Gupta NG, PK Daman, A Choudhary, 2023. Enzymes in the food sector: Current applications. Agricos e-Newslet., 4: 19.
Sekhon B and MK Sangha, 2004. Detergents—zeolites and enzymes excel cleaning power. Resonan., 9: 35-45.
Sharma B, AK Dangi and P Shukla, 2018. Contemporary enzyme based technologies for bioremediation: a review. J. Environ. Manage., 210: 10-22.
Šibalić D, A Šalić, AJ Tušek, T Sokač, K Brekalo, B Zelić, NN Tran, V Hessel and M Tišma, 2020. Sustainable production of lipase from *Thermomyces lanuginosus*: process optimization and enzyme characterization. Ind. Eng. Chem. Res., 59: 21144-21154.
Singh R, R Das, S Sangwan, B Rohatgi, R Khanam, SPG Peera, S Das, YA Lyngdoh, S Langyan and A Shukla, 2021. Utilisation of agro-industrial waste for sustainable green production: a review. Environ. Sustain., 4: 619-636.
Singh R, M Kumar, A Mittal and PK Mehta, 2016. Microbial enzymes: industrial progress in 21st century. 3 Biotech ., 6: 1-15.
Skals PB, A Krabek, PH Nielsen and H Wenzel, 2008. Environmental assessment of enzyme assisted processing in pulp and paper industry. Int. J. Life Cycle Assess., 13: 124-132.
Thapa S, H Li, J OHair, S Bhatti, FC Chen, KA Nasr, T Johnson and S Zhou, 2019. Biochemical characteristics of microbial enzymes and their significance from industrial perspectives. Mol. Biotechnol., 61: 579-601.
Toldra F and SK Kim, 2016. Marine enzymes biotechnology: production and industrial applications, marine organisms producing enzymes, Academic Press.
Trono D, 2019. Recombinant enzymes in the food and pharmaceutical industries. In: Advances in enzyme technology. Edited by: Singh RS, RR Singhania, C Larroche, Elsevier., pp. 349-387.
Uddin M, J Taweekun, K Techato, M Rahman, M Mofijur and M Rasul, 2019. Sustainable biomass as an alternative energy source: Bangladesh perspective. Ener. Proced., 160: 648-654.
Vandamme E, S De Baets, A Vanbaelen, K Joris and P De Wulf, 1998. Improved production of bacterial cellulose and its application potential. Polym. Degrad. Stab., 59: 93-99.
Vardhan KH, PS Kumar and RC Panda, 2019. A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. J. Mol. Liq., 290: 111197.
Velasco-Lozano S, T Volke-Sepulveda and E Favela-Torres, 2012. Lipases production by solid-state fermentation: the case of *Rhizopus homothallicus* in perlite. Lip. Phosphol. Met. Prot., 1: 227-237.

Vogel A, 2019. Enzyme development technologies. In: Industrial enzyme applications. Edited by: Vogel A, O May, Wiley online Library, pp. 25-45.

Wang B, F Dong, M Chen, J Zhu, J Tan, X Fu, Y Wang and S Chen, 2016. Advances in recycling and utilization of agricultural wastes in China: Based on environmental risk, crucial pathways, influencing factors, policy mechanism. Procedia. Environ. Sci., 31: 12-17.

Wang J, L Jiang and H Sun, 2021. Early evidence for beer drinking in a 9000-year-old platform mound in southern China. Plos One, 16: e0255833.

Wellenbeck W, J Mampel, C Naumer, A Knepper and P Neubauer, 2017. Fast-track development of a lactase production process with *Kluyveromyces lactis* by a progressive parameter-control workflow. Eng. Life Sci., 17: 1185-1194.

West TP, 2023. Citric acid production by *Aspergillus niger* using solid-state fermentation of agricultural processing coproducts. Appl. Biosci., 2: 1-13.

Wing LA, 2022. Graduating LDC status: Braving challenges and the way forward for Bangladesh. Available: https://www.lightcastlebd.com/.

Winkler CK, JH Schrittwieser and W Kroutil, 2021. Power of biocatalysis for organic synthesis. ACS. Cent. Sci., 7: 55-71.

Wong CM, KH Wong and XD Chen, 2008. Glucose oxidase: natural occurrence, function, properties and industrial applications. Appl. Microbiol. Biotechnol., 78: 927-938.

Wu P, F Luo, Z Lu, Z Zhan and G Zhang, 2020. Improving the catalytic performance of pectate lyase through pectate lyase/$Cu_3(PO_4)_2$ hybrid nanoflowers as an immobilized enzyme. Front. Bioeng. Biotechnol., 8: 280.

Xiao YZ, DK Wu, SY Zhao, WM Lin and XY Gao, 2015. Statistical optimization of alkaline protease production from *Penicillium citrinum* YL-1 under solid-state fermentation. Prep. Biochem. Biotechnol., 45: 447-462.

Xu Z, H He, S Zhang, T Guo and J Kong, 2017. Characterization of feruloyl esterases produced by the four lactobacillus species: *L. amylovorus, L. acidophilus, L. farciminis* and *L. fermentum*, isolated from ensiled corn stover. Front. Microbiol., 8: 941.

Yadav A, AAM Ali, M Ingawale, S Raychaudhuri, LM Gantayet and A Pandit, 2020. Enhanced co-production of pectinase, cellulase and xylanase enzymes from *Bacillus subtilis* ABDR01 upon ultrasonic irradiation. Process. Biochem., 92: 197-201.

Yafetto L, 2022. Application of solid-state fermentation by microbial biotechnology for bioprocessing of agro-industrial wastes from 1970 to 2020: A review and bibliometric analysis. Heliyon, 24: 8:e09173.

Yee C, 2018. Peli bio-chem to set up production unit in Bangladesh in near future. Available: https://www.textiletoday.com.bd/peli-bio-chem-set-production-unit-bangladesh-near-future.

Zambare V, 2011. Optimization of amylase production from *Bacillus Sp*. using statistics based experimental design. Emir. J. Food Agri., 23: 37-47.

Zhang Y, T Geary and BK Simpson, 2019. Genetically modified food enzymes: a review. Curr. Opin. Food Sci., 25: 14-18.