International Journal of Environment, Agriculture and Biotechnology
Vol-10, Issue-5; Sep-Oct, 2025
Peer-Reviewed International Journal
Journal Home Page Available: https://ijeab.com/
Journal DOI: 10.22161/ijeab

Smart Extremozymes: The Next-Generation Biocatalysts for Sustainable Industrial Wastewater Management

Tejas B. Chaudhari[1], Tushar A. Shinde[2], Leena P. Shirsath[1], Sandip P. Patil[1,*]

[1] Department of Microbiology and Biotechnology, R. C. Patel Arts, Commerce and Science College, Shirpur-425405, India
[2] SVKM's NMIMS University, MPSTME, Centre for Textile Functions, Shirpur-425405, India
[*]Corresponding author: patilsandip3@gmail.com

Received: 12 Sep 2025; Received in revised form: 10 Oct 2025; Accepted: 16 Oct 2025; Available online: 25 Oct 2025

***Abstract*— Industrial wastewater treatment face various challenges like high pollutant load, extreme environmental conditions and the need for cost-effective and eco-friendly solutions. These challenges could be sustainably managed using biocatalysts like enzymes. Although enzymes are sustainable approach towards this, but they often act futile due to the extreme conditions present in the wastewater. Extremozymes are specialized enzymes with the ability to function under extreme conditions and offer a promising approach to address these challenges. The types of extremozymes explored in this study include thermozymes, psychrozymes, halozymes, alkalozymes and acidozymes. Their mechanism of action enables the efficient breakdown of pollutants making them highly suitable for industrial applications. Extremozymes have proven effective in treating effluents from industries such as textiles, pulp and paper, pharmaceuticals and food. These enzymes provide high stability and efficiency in harsh wastewater environments. Moreover, these enzymes also offer advantages such as reduced operational costs and minimized environmental footprints. Recent advancements such as AI-driven enzyme design, synthetic biology and nano-immobilization strategies have further enhanced extremozyme performance which leads to the development of intelligent and reusable "bionanoextremozymes" capable of functioning efficiently under fluctuating industrial conditions. By leveraging extremozymes, industries can adopt a more sustainable and efficient approach to wastewater treatment. This review highlights their potential to revolutionize industrial effluent management, paving the way for sustainable, environmentally friendly and economically viable wastewater treatment solutions.*

Keywords*— Biocatalyst, Extremozymes, Industry, Sustainability, Wastewater

I. INTRODUCTION

Industrial wastewater poses significant challenges due to its diverse composition and environmental impacts. It contains a mix of organic pollutants, heavy metals, toxic chemicals and nutrients that can harm ecosystems and human health [1]. This content in wastewater varies depending on the type of industry. The high volumes of discharge from industries such as textiles, pharmaceuticals and food processing intensify the problem. Untreated wastewater contributes to water pollution, soil pollution and eutrophication that enhances the disruption of ecosystems and agricultural productivity [2]. Meeting stringent regulatory requirements demands advanced treatment methods. Whereas conventional processes like coagulation and activated sludge systems are often energy-intensive and costly. The demand for sustainability has added pressure to recover resources such as water, nutrients and energy from wastewater. Climate change further complicates wastewater management by impacting water availability and quality. Hence, these challenges need to be addressed. Furthermore, certain pollutants like synthetic dyes and heavy metals resist traditional treatments. This necessitates the development of innovative approaches such as membrane filtration, advanced oxidation processes and bioremediation utilizing metabolites like enzymes [3]. Enzymes represent a sustainable and environmentally friendly solution for wastewater treatment, as they operate without requiring external energy input [4]. However, conventional enzymes often lose functionality under extreme environmental conditions like high pH or temperature [5]. This necessitates the need for alternative strategies that are effective in such challenging extreme conditions. Extremozymes derived from extremophiles exhibit remarkable stability and activity under harsh industrial conditions. These specialized enzymes can enhance wastewater treatment processes by efficiently utilizing recalcitrant pollutants as substrate. This can build up an enzyme-substrate (ES) complex enhancing the velocity of ES reaction to maximum [6]. Hence, this can be effectively used in wastewater treatment without any effect of harsh environmental conditions [7].

Extremozymes are specialized enzymes produced by extremophilic microorganisms that thrive in extreme conditions such as high temperature, salinity and acidity. These enzymes are highly stable and maintain their catalytic activity under harsh industrial environments and hence they remain a sustainable approach for wastewater treatment [8]. Extremozymes effectively degrade recalcitrant pollutants like synthetic dyes, hydrocarbons and heavy metal complexes [9]. These pollutants are resistant to conventional methods. Furthermore, extremozymes support sustainability by enabling the biodegradation of pollutants without producing harmful byproducts aligning with eco-friendly practices [10]. They can also be incorporated into advanced treatment technologies like bioreactors or enzymatic membranes.

II. ROLE OF EXTREMOZYMES IN SUSTAINABLE WASTEWATER TREATMENT

Extremozymes play a pivotal role in sustainable wastewater treatment by enhancing the efficiency and eco-friendliness of the process. Derived from extremophiles, these enzymes remain active under harsh industrial conditions where conventional enzymes fail. This resilience allows extremozymes to degrade recalcitrant pollutants including synthetic dyes, hydrocarbons and toxic chemicals that are resistant to traditional methods [7]. Conventional enzymes need extensive energy inputs to adjust optimum pH and temperature in their production and purification process to maintain the performance [11]. However, the unique ability to operate without any temperature or pH adjustments makes the use of extremozymes cost-effective and energy efficient [12]. By reducing the reliance on chemical-intensive processes and aligning with circular economy principles, extremozymes contribute significantly to resource recovery that includes clean water and reusable byproducts. Their application represents a shift towards greener and more sustainable industrial wastewater management practices. This addresses the dual challenges of pollution control and resource conservation.

Types of Extremozymes used in Wastewater Management

The unique properties of extremozymes make them valuable in wastewater management, as they efficiently degrade a wide range of pollutants even in harsh environments. Different types of extremozymes include thermostable, halotolerant, acidophilic and alkaliphilic enzymes [13]. These enzymes target various contaminants based on the specific conditions of industrial wastewater. Understanding these types and their applications enables tailored solutions for efficient and sustainable wastewater treatment. The major types of extremozymes used in wastewater treatment are discussed in the following Fig. 1.

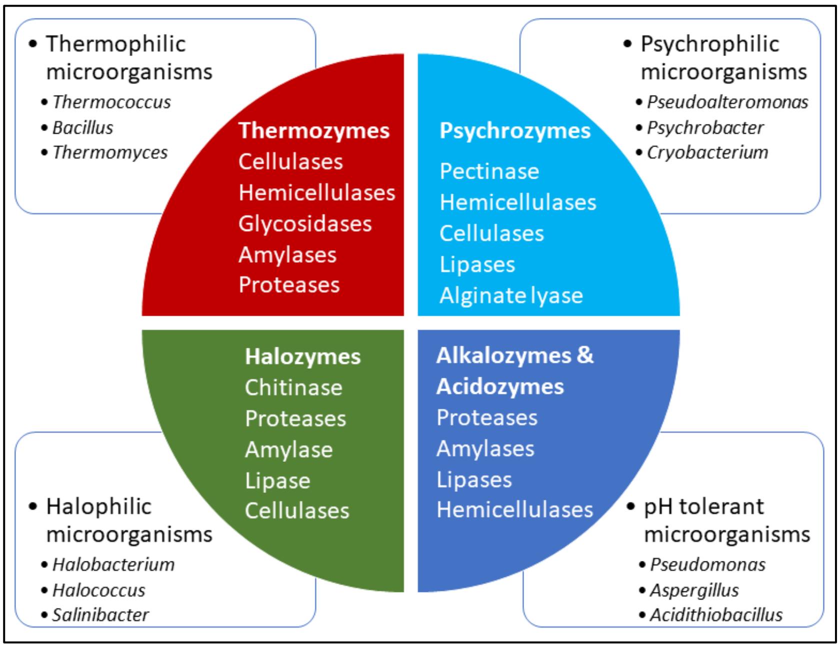

Fig. 1. Types of extremozymes used in wastewater treatment

2.1 Thermozymes

Thermozymes are enzymes derived from thermophilic microorganisms that thrive at elevated temperatures typically ranging from 50°C to 80°C or higher. These enzymes exhibit remarkable thermal stability by retaining their catalytic activity under high-temperature conditions commonly found in industrial wastewater treatment processes. Their ability to function efficiently at high temperatures eliminates the need for extensive cooling systems and hence reduces energy costs and enhancing process efficiency. Thermozymes also accelerate the biodegradation of recalcitrant pollutants like dyes and phenolic compounds that are resistant to conventional methods [14]. Moreover, high-temperature operations facilitated by thermozymes minimize the risk of microbial contamination and enhance reaction rates that make these processes faster and more effective. They are particularly useful in industries like textiles, pulp and paper and food processing in which hot effluents are common. Many of the thermozymes are cellulases, hemicellulases, glycosidases, pullulanases, proteases etc. Examples of thermophilic microorganisms producing these enzymes include *Thermococcus*, *Bacillus* and *Thermomyces* etc. [13].

2.2 Psychrozymes

Psychrozymes are enzymes produced by psychrophilic microorganisms that thrive in cold environments typically at temperatures below 15°C. These enzymes retain their catalytic activity and stability at low temperatures that makes them highly effective for wastewater treatment in cold climates or processes involving low-temperature effluents. In wastewater management, psychrozymes are particularly valuable for industries where heating is impractical or unaffordable [15]. They efficiently degrade organic pollutants such as proteins, fats and carbohydrates in cold conditions, ensuring effective treatment without the need for energy-intensive temperature adjustments. Their functionality at low temperatures also minimizes the risk of thermal denaturation that ensures prolonged enzyme activity and reduces operational costs. Psychrozymes are instrumental in the treatment of low-temperature effluents from industries like dairy, food processing and breweries where conventional enzymes often lose effectiveness [16]. They are also advantageous in municipal wastewater systems in cold regions in which ambient temperatures can hinder biological treatment processes. Their eco-friendly operation aligns with the goals of reducing carbon footprints and operational costs that make them an essential tool for industries and regions aiming to optimize the process in challenging cold environments. Some psychrozymes include cold-active polygalacturonase, α-amylase, phosphatase, proteases etc. Examples of psychrophilic microorganisms producing these enzymes include *Pseudoalteromonas*, *Psychrobacter* and *Cryobacterium* [17].

2.3 Halozymes

Halozymes are specialized enzymes produced by halophilic microorganisms that thrive in high-salt environments. These enzymes retain their catalytic activity and stability under saline conditions that make them invaluable for treating wastewater with elevated salt concentrations. Effluents from industries like textiles, tanning, oil and gas and seafood processing releases wastewater that is high in salt concentration. Haloenzymes can be an effective approach to treat such kinds of wastewater effluents. Conventional enzymes and microbial systems often lose efficiency in saline wastewater due to osmotic stress and denaturation [18]. In contrast, halozymes are naturally adapted to such environments that enable efficient degradation of organic pollutants like proteins, lipids and hydrocarbons in saline effluents. Their functionality helps reduce the biological oxygen demand (BOD) and chemical oxygen demand (COD) of wastewater. Halozymes also support advanced treatment methods like enzymatic bioreactors and membrane technologies by maintaining activity under saline conditions [19]. This adaptability reduces the need for costly desalination or chemical adjustments that makes the process more cost-effective and sustainable. Furthermore, the use of halozymes aligns with eco-friendly practices that minimize the need for harsh chemicals in saline wastewater treatment. By leveraging the unique properties of halozymes, industries can effectively manage saline effluents. Some common halozymes include Halophilic proteases, lipases, amylases, esterases, dehydrogenases, etc. These halozymes are typically derived from halophilic microorganisms such as *Halobacterium*, *Halococcus* and *Salinibacter* [20].

2.4 Alkalozymes

Alkalozymes are particularly effective in degrading pollutants in alkaline wastewater from textile, paper, detergent and tannery industries. They catalyze the breakdown of recalcitrant compounds like synthetic dyes, lignin derivatives and industrial chemicals, ensuring efficient detoxification [21]. Their ability to withstand and operate in high pH conditions eliminates the need for chemical neutralization. Some major alkalozymes include alkaline proteases, lipases and amylases that are widely used for breaking down proteins, fats and starch present in alkaline wastewater [22]. Several microorganisms produce alkalozymes. Some of the prominent examples of alkalozymes producing microorganisms include *Bacillus*, *Pseudomonas*, *Aspergillus* etc. [13].

2.5 Acidozymes

Acidozymes play a crucial role in treating acidic effluents from industries like mining, battery manufacturing and food processing. These enzymes degrade pollutants such as organic acids, heavy metals and sulfates that are prevalent in acidic wastewater. By functioning directly in low pH environments, acidozymes eliminate the need for pH adjustments by reforming the treatment process. Examples of acidozymes include acidic proteases, amylases and lipases that facilitate the breakdown of proteins, starch and fats respectively in acidic effluents. Acidophilic microorganisms such as *Acidithiobacillus*, *Aspergillus* and *Fusarium* are common producers of acidozymes [23].

III. MECHANISM OF ACTION OF EXTREMOZYMES

Extremozymes operate under extreme environmental conditions such as high or low temperatures, pH or salinity. Their mechanism of action in wastewater treatment involves breaking down complex pollutants into simpler and non-toxic compounds to enhance the efficiency of the treatment process. The extremozymes have a specific mode of action by which they act against the pollutants present in wastewater. Like every enzyme, extremozymes also have specialized active sites that bind to specific pollutants present in wastewater. This step is called substrate binding. Extremozymes interact with these substrates through non-covalent forces that form enzyme-substrate complex which is followed by catalysis. Once bound, extremozymes catalyze the breakdown of complex pollutants into simpler and biodegradable products. In the case of industrial pollutants like dyes or phenolic compounds, extremozymes like laccases and peroxidases initiate oxidation reactions [18]. This leads to the decolorization and detoxification of these pollutants. The extremophilic ability of extremozymes is achieved through structural adaptations like increased hydrophobic interactions and stronger enzyme-substrate binding. This prevents denaturation and ensures prolonged activity even in harsh wastewater environments. Through their catalytic action, extremozymes effectively degrade toxic and recalcitrant pollutants into less harmful substances (Fig. 2). This action often converts them into water-soluble and biodegradable compounds. This reduces the toxicity of the effluent and hence makes it safer for discharge or further treatment [24]. Extremozymes contribute to more sustainable wastewater management by reducing the need for harmful chemicals and energy-intensive processes like heating or pH adjustment.

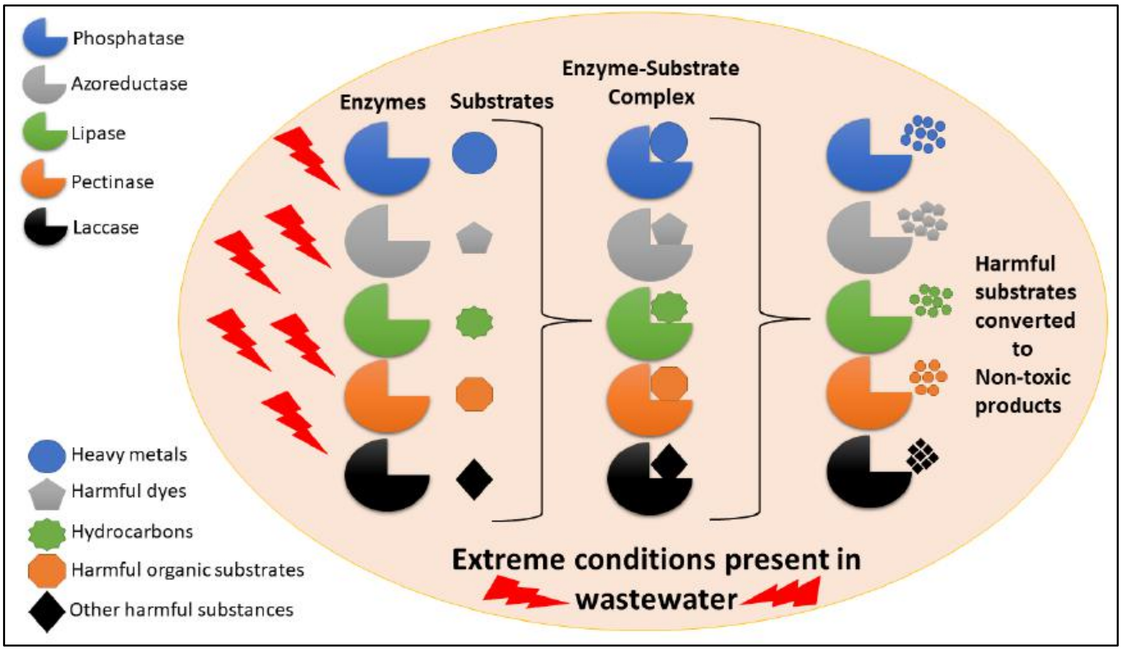

Fig. 2. Mechanism of action of extremozymes in wastewater treatment

IV. APPLICATIONS OF EXTREMOZYMES IN INDUSTRIAL WASTEWATER TREATMENT

4.1 Textile Industry Effluents

The textile industry generates effluents containing high levels of synthetic dyes, organic pollutants, salts and heavy metals. These effluents are often resistant to biodegradation due to the presence of azo bonds and aromatic rings in dyes. Extremozymes like laccases and peroxidases (manganese peroxidase and lignin peroxidase) play a pivotal role in treating such effluents (Fig. 3). Laccases catalyze the oxidation of phenolic and non-phenolic compounds by breaking down dye molecules into less toxic fragments [9]. While peroxidases use hydrogen peroxide to cleave azo bonds by transforming colored compounds into colorless by-products. Moreover, their efficiency is enhanced by redox mediators that enables the degradation of complex dyes.

4.2 Paper and Pulp Industry Effluents

Effluents from the paper and pulp industry are characterized by high chemical oxygen demand (COD). It contains high amounts of lignin, cellulose, hemicellulose and chlorinated organic compounds that pose significant environmental concerns [25] (Fig. 3). Extremozymes such as xylanases, cellulases and ligninases play a crucial role in addressing these issues. Ligninases like lignin peroxidase and manganese peroxidase degrade lignin into smaller phenolic compounds, reducing toxicity. Xylanases and cellulases hydrolyze cellulose and hemicellulose into simpler sugars and enhance their biodegradability [26]. Additionally, xylanases minimize the use of harsh chemicals like chlorine in bleaching thereby reducing chlorinated by-products [27]. These enzymes are integrated into pulping and effluent treatment processes to promote sustainable practices by reducing COD and improving effluent quality.

4.3 Pharmaceutical Industry Effluents

The pharmaceutical industry effluents are characterized by high concentrations of antibiotics, active pharmaceutical ingredients (APIs), organic solvents and heavy metals. Along with this, persistent bioactive compounds that pose significant risks to ecosystems are also present in these effluents. Extremozymes such as P450 monooxygenases, lipases and nitrilases play a crucial role in addressing these pollutants (Fig. 3). P450 monooxygenases catalyze oxidation reactions by breaking down complex APIs into inactive or biodegradable metabolites. Lipases hydrolyze fatty and ester-based pollutants thereby mitigating their bioactivity. While nitrilases detoxify nitrile groups by converting them into non-toxic carboxylic acids and ammonia [19].

4.4 Food Industry Effluents

Effluents from the food industry are characterized by high levels of organic matter like fats-oils-grease (FOG), starch, proteins and variable pH that may be acidic or alkaline. Extremozymes such as proteases, amylases, lipases and pectinases are effectively used to treat these effluents. Amylases hydrolyze starch into simpler sugars (Fig. 3). This reduces biological oxygen demand (BOD) and chemical oxygen demand (COD). Proteases break down proteins into peptides and amino acids. While lipases convert fats and oils into glycerol and free fatty acids and reduce FOG accumulation. These extremozymes operate efficiently under the challenging pH conditions of food waste that helps in enhancing biodegradability in effluent treatment plants.

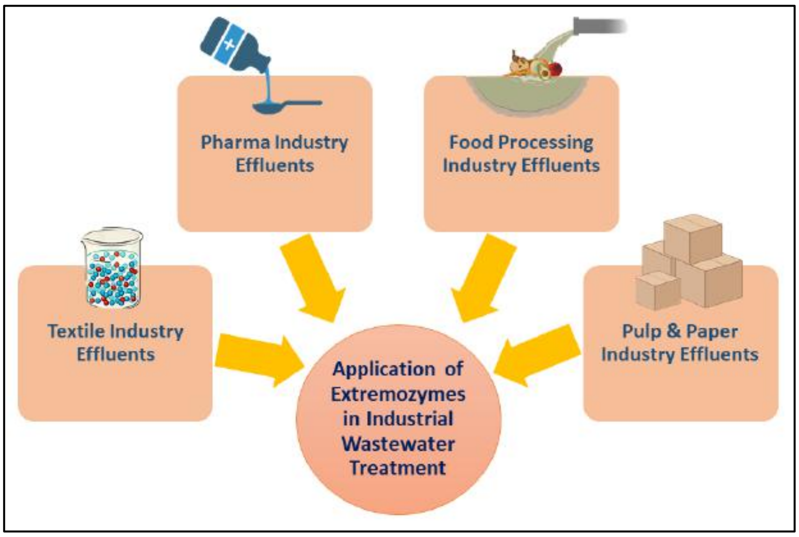

Fig. 3. Applications of Extremozymes in Industrial Wastewater Treatment

V. ADVANTAGES OF USING EXTREMOZYMES

Extremozymes are exceptionally stable and active under extreme conditions like high temperatures, extreme pH levels and high salinity that are often encountered in industrial effluents. Unlike conventional enzymes, extremozymes maintain their catalytic efficiency under harsh conditions that reduce the need for stringent control measures during treatment processes. This stability allows for prolonged operational cycles, decreasing enzyme replacement frequency and lowering costs [28]. Moreover, extremozymes facilitate the breakdown of complex and recalcitrant pollutants that help in enhancing the degradation of industrial waste. Their ability to function in diverse environments makes them ideal for bioremediation strategies [29]. This contributes to sustainable and eco-friendly wastewater management.

VI. FUTURE PROSPECTS

The next frontier in wastewater bioremediation lies in the integration of computational enzyme design, synthetic biology and nanotechnology to create intelligent and highly efficient extremozyme systems. Artificial intelligence (AI) and machine learning algorithms have revolutionized protein engineering by enabling the prediction of enzyme structures, stability and catalytic efficiency under diverse conditions. AI-based platforms such as AlphaFold and Resetta can be employed to model the active sites of extremozymes and predict mutations that enhance their thermostability, halotolerance and pH resilience. This rational enzyme design approach can lead to the development of smart extremozymes capable of dynamically adapting to the fluctuating physicochemical properties of industrial wastewater. Synthetic biology further strengthens this concept by facilitating the construction of hybrid or chimeric extremozymes that combine multiple stress-tolerance traits, expanding their applications across different industrial effluent systems.

Parallelly, the immobilization of extremozymes on nanomaterials introduces another promising strategy for improving their stability, reusability and catalytic efficiency. Nano carriers like magnetic nanoparticles, graphene oxide, mesoporous silica and metal organic frameworks provide a high surface area and functional groups that promote stable enzyme binding. These nano-immobilized systems exhibit enhanced resistance to denaturation and can be easily recovered magnetically which reduces operational costs. Furthermore, nanocarrier-assisted immobilization minimizes enzyme leaching and allows continuous treatment in bioreactors. The combination of extremozymes with nanotechnology not only prolongs their functional lifespan but also aligns with circular bioeconomy principles by enabling enzyme reuse and waste valorization.

VII. CONCLUSION

The use of extremozymes in industrial wastewater treatment presents a sustainable and cost-effective solution for addressing the challenges posed by harsh environmental conditions and complex pollutants. Their exceptional stability, efficiency and adaptability under extreme conditions make them superior to conventional enzymes. By integrating extremozymes into wastewater treatment processes, industries can achieve efficient remediation while reducing environmental impact and operational costs and thereby promoting a greener and more sustainable approach to waste management. Furthermore, the emergence of AI-driven enzyme design, synthetic biology and nano-immobilization strategies has opened new horizons in extremozyme research and application. These cutting-edge approaches enable the development of “smart extremozymes” and “bionanoextremozymes” with enhanced catalytic resilience, reusability and adaptability to dynamic wastewater conditions. The convergence of these technologies will likely revolutionize the field of biocatalytic wastewater management, driving the transition from conventional treatment systems toward intelligent, self-optimizing and sustainable biorefinery-based solutions for a cleaner environment.

ACKNOWLEDGEMENTS

The authors acknowledge the management and Principal of R. C. Patel Arts, Commerce and Science College, Shirpur for providing research infrastructure.

REFERENCES

[1] Mathew N, Somanathan A, Tirpude A, Arfin T. The impact of short-lived climate pollutants on the human health. *Environ Pollut Manag*. 2024; 1: 1-14. https://doi.org/10.1016/j.epm.2024.04.001.

[2] Akpor OB, Otohinoyi DA, Olaolu DT, Aderiye BI. Pollutants in wastewater effluents: impacts and remediation processes. *Int J Environ Res Earth Sci*. 2014; 3(3): 50-59. https://eprints.lmu.edu.ng/id/eprint/1023.

[3] Patil AM, Mahashabde JP, Shirsath LP, Shinde TA, Patil SP. Keratinase enzyme production from *Bacillus licheniformis* KP9 isolated from chicken feathers. *J Sci Res.* 2021; 65: 24-28. https://doi.org/10.37398/JSR.2021.650706.

[4] Liu Z, Smith SR. Enzyme recovery from biological wastewater treatment. Waste Biomass Valor. 2021; 12: 4185-4211. https://doi.org/10.1007/s12649-020-01251-7.

[5] Patil SP, Shirsath LP, Chaudhari BL. A halotolerant hyaluronidase from newly isolated *Brevibacterium halotolerans* DC1: purification and characterization. Int J Biol Macromol. 2021; 166: 839-850. https://doi.org/10.1016/j.ijbiomac.2020.10.240.

[6] Patil S, Bhadane B, Shirsath L, Patil R, Chaudhari B. Steroidal fraction of *Carissa carandas* L. inhibits microbial hyaluronidase activity by mixed inhibition mechanism. Prep Biochem Biotechnol. 2019; 49: 298-306. https://doi.org/10.1080/10826068.2018.1541811.

[7] Atif F, Maqsood N, Ali W, Irfan M. Extremophiles and their enzymatic diversity and biotechnological potential. SMAB. 2024; 4: 833–849. https://doi.org/10.1007/s43393-024-00275-7.

[8] Patil S, Chaudhari B. A simple, rapid and sensitive plate assay for detection of microbial hyaluronidase activity. J

Basic Microbiol. 2017; 57: 358-361. https://doi.org/10.1002/jobm.201600579.

[9] Kakkar P, Wadhwa N. Extremozymes used in textile industry. J Text Inst. 2022; 113: 2007-2015. https://doi.org/10.1080/00405000.2021.1948251.

[10] Gallo G, Aulitto M. Advances in extremophile research: biotechnological applications through isolation and identification techniques. Life. 2024; 14(9): 1205. https://doi.org/10.3390/life14091205.

[11] Patil SP, Dalal KS, Shirsath LP, Chaudhari BL. Microbial hyaluronidase: its production, purification and applications. In: Industrial Microbiology and Biotechnology: Emerging Concepts in Microbial Technology. Singapore: Springer Nature Singapore; 2023: 473-497. https://doi.org/10.1007/978-981-99-2816-3-16.

[12] Kumari M, Karn SK, Raj V. Extremophiles and related extremozymes: their structure-function relationship in industrial applications. Ind Biotechnol. 2024; 20(6): 279-295. https://doi.org/10.1089/ind.2024.0029.

[13] Espliego JME, Saiz VB, Torregrosa-Crespo J, Luque AV, Carrasco MLC, Pire C, et al. Extremophile enzymes and biotechnology. In: Extremophiles. CRC Press; 2018: 227-248. https://surl.li/rpbhus.

[14] Pham VHT, Kim J, Chang S, Bang D. Investigating bio-inspired degradation of toxic dyes using potential multi-enzyme producing extremophiles. Microorganisms. 2023; 11(5): 1273. https://doi.org/10.3390/microorganisms11051273.

[15] Gupta V, Bhaskar P, Thoudam J, Bisht S, Sharma A, Tripathi R. Psychrophiles as a novel and promising source of cold-adapted industrial enzymes. 2023; 4(2): 54-68. https://doi.org/10.52679/tabcj.2023.0006.

[16] Annapure US, Nair P. Psychrozymes: a novel and promising resource for industrial applications. In: Microbial Extremozymes. Academic Press; 2022: 185-95. https://doi.org/10.1016/B978-0-12-822945-3.00018-X.

[17] Hamid B, Bashir Z, Yatoo AM, Mohiddin F, Majeed N, Bansal M, et al. Cold-active enzymes and their potential industrial applications - a review. Molecules. 2022; 27(18): 5885. https://doi.org/10.3390/molecules27185885.

[18] Kumar A, Singh AK, Bilal M, Chandra R. Extremophilic ligninolytic enzymes: versatile biocatalytic tools with impressive biotechnological potential. Catal Lett. 2021; 152: 1-25. https://doi.org/10.1007/s10562-021-03800-8.

[19] Narang AS, Krause EMSP, Yee JC. Biologic drug substance and drug product manufacture. In: Pharmaceutical Inhalation Aerosol Technology. CRC Press; 2019: 205-32. https://surl.li/zinhps.

[20] Das D, Kalra I, Mani K, Salgaonkar BB, Braganca JM. Characterization of extremely halophilic archaeal isolates from Indian salt pans and their screening for production of hydrolytic enzymes. Environ Sustain. 2019; 2: 227-239. https://doi.org/10.1007/s42398-019-00077-x.

[21] Chinnathambi A. Industrial important enzymes from alkaliphiles - an overview. Biosci Biotechnol Res Asia. 2015; 12: 2007-2016. http://dx.doi.org/10.13005/bbra/1868.

[22] Kanekar PP, Kanekar SP. Alkaliphilic, alkalitolerant microorganisms. In: Diversity and Biotechnology of Extremophilic Microorganisms from India. Singapore: Springer Nature Singapore; 2022: 71-116. https://doi.org/10.1007/978-981-19-1573-4.

[23] Tiquia-Arashiro S, Rodrigues DF. Alkaliphiles and acidophiles in nanotechnology. In: Tiquia-Arashiro S, Rodrigues D, editors. Extremophiles: Applications in Nanotechnology. 2016: 129-62. https://doi.org/10.1007/978-3-319-45215-9-4.

[24] Elleuche S, Schäfers C, Blank S, Schröder C, Antranikian G. Exploration of extremophiles for high temperature biotechnological processes. Curr Opin Microbiol. 2015; 25: 113-119. https://doi.org/10.1016/j.mib.2015.05.011.

[25] Patil SP, Chaudhari TB, Dalal KS, Phirke NV, Chaudhari BL. Laccase-mediated valorization of lignocellulosic biomass: an eco-friendly approach towards the sustainable environment. In: Industrial Microbiology and Biotechnology: A New Horizon of the Microbial World. Singapore: Springer Nature Singapore; 2024: 635-661. https://doi.org/10.1007/978-981-97-6270-5_21.

[26] Wang J, Liang J, Li Y, Tian L, Wei Y. Characterization of efficient xylanases from industrial-scale pulp and paper wastewater treatment microbiota. AMB Express. 2021; 11: 1-11. https://doi.org/10.1186/s13568-020-01178-1.

[27] de Souza MF, Teixeira RSS, da Silva ASA, Ferreira-Leitão VS, da Silva Bon EP. Chlorine-free biomass processing: enzymatic alternatives for bleaching and hydrolysis of lignocellulosic materials. In: Chem Beyond Chlor. 2016: 241-268. https://doi.org/10.1007/978-3-319-30073-3_8.

[28] Mao S, Jiang J, Xiong K, Chen Y, Yao Y, Liu L, et al. Enzyme engineering: performance optimization, novel sources and applications in the food industry. Foods. 2024; 13: 3846. https://doi.org/10.3390/foods13233846.

[29] Gomes J, Walter S. The biocatalytic potential of extremophiles and extremozymes. Food Technol Biotechnol. 2004; 42: 223-225. https://hrcak.srce.hr/110869.