Available online on 15.10.2025 at http://ajprd.com

Asian Journal of Pharmaceutical Research and Development

Open Access to Pharmaceutical and Medical Research

Open Access **Review Article**

Role of Bioenzyme as Catalyst for Sustainable Chemistry

Ghuge Samiksha K, Khaire Rahul, Kathale Ankita A, Sankhe Lochani D, Bhandare Tejaswini S, Koade Payal B

Pravara Rural Education Society's College of Pharmacy (for Women), Chincholi, Nashik, Maharashtra, India

A B S T R A C T

The integration of bio enzymes as catalysts represents a pivotal strategy for advancing sustainable chemistry. Enzymes, as natural biocatalysts, offer high specificity, operate under mild conditions, and generate minimal by-products, aligning closely with the principles of green chemistry. Their biodegradability, renewability, and compatibility with aqueous systems enable environmentally friendly processes across pharmaceutical, food, textile, and chemical industries. Innovations in enzyme engineering, bioinformatics, and artificial intelligence have enhanced catalytic efficiency and stability, expanding enzyme applications to include nanozymes and tailored industrial bioprocesses. Immobilization techniques—such as adsorption, encapsulation, covalent bonding, and cross-linking—further improve enzyme reusability and cost-effectiveness, addressing industrial demands. Emerging fields like metagenomics facilitate the discovery of novel enzymes from uncultured microorganisms, unlocking new biocatalytic pathways. Bio enzyme-based treatments also provide eco-efficient solutions for wastewater remediation by degrading organic pollutants and reducing heavy-metal content. Together, these developments underscore the transformative role of bio enzymes in replacing traditional chemical reagents, minimizing waste, and reducing energy inputs. By coupling biotechnology with sustainable chemical practices, bio enzymes stand as a cornerstone for a greener, circular economy and the realization of global sustainability goals.

Keywords: Biocatalyst, Green chemistry, Sustainable chemistry, Nano enzymes, Immobilization, Metagenomics.

A R T I C L E I N F O: Received 24 March 2025; Review Complete 18 May 2025; Accepted 18 August 2025. ; Available online 15 Oct. 2025

Cite this article as:

Ghuge SK, Khaire Rahul D, Kathale AA, Sankhe LD, Bhandare TS, Koade PB, Role of Bioenzyme as Catalyst for Sustainable Chemistry, Asian Journal of Pharmaceutical Research and Development. 2025; 13(5):83-88,DOI: http://dx.doi.org/10.22270/ajprd.v13i5.1630

*Address for Correspondence:

Ghuge Samiksha K, Pravara Rural Education Society's College of Pharmacy (for Women), Chincholi, Nashik, Maharashtra, India

INTRODUCTION:

The operation of nature's catalysts, the enzymes, for executing sustainable processes is gaining growing significance and is in a good position to take a commanding part towards the consummation of the European Union's sustainable development thing as well as encyclopedically. The European Commission, via the European Green Deal, will put EU frugality on the path to a more sustainable future and will promote the United Nations' 2030 Agenda. The operation biocatalystsare a vital element of this operation of' green chemistry' for reaching the target of eco-friendly artificial processes with optimal application of coffers and reduced generation of waste in an indirect bio-based frugality [1]. The field of biocatalysts and enzyme engineering has gained elevation as a crucial motorist of sustainable chemical processes. With adding environmental regulations and a global drive towards greener technologies, biocatalystsoffer a promising alternative to conventional chemical transformation styles. Enzymes, as natural catalysts, retain unique parcels similar to high particularity, mild response conditions, and minimum by-products, which make them ideal for environmentally friendly processes. Enzyme engineering further enhances these attributes by optimizing enzyme performance and acclimatizing their exertion for specific artificial operations. This preface sets the stage for an in-depth examination of how biocatalysts and enzyme engineering contribute to green chemical metamorphoses, focusing on recent advancements and unborn prospects [2]. Enzymes are applied in most environmental-friendly industrial applications since they are efficient, selective, accelerate and increase the rate of reactions by creating transition state complexes with their substrate, which decreases the activation energy of the reaction. Progress in biotechnology, particularly in the field of genetics and protein engineering, has revealed a new era of enzyme applications in various industrial processes and undergoing significant R&D efforts, leading not only to the creation of a series of new products but betterment in the process and performance of various processes already established. Enzymes find applications in many areas of application such as food and feed stuff manufacturing, cosmetics, pharmaceutical products and as a research and development tool. Technical enzymes find uses in detergents, pulp and paper uses, textile manufacturing, leather production, for fuel and for the manufacture of pharmaceuticals and chemical compounds in the chemical industry. Enzyme application in animal feeding is significant and increasing, particularly for pig and poultry feeding. Feed enzymes provide the advantage of hydrolyzing particular components of the feed that are otherwise toxic or without any value to the animals. In cosmetic products, it is applied to is skin peeling, and potential uses can include skin protection. Outstanding enzymatic medicines include as a digestive, wound debridement, lysis of thromboses in veins, acute treatment of myocardial infarction and as an adjuvant to the treatment of some forms of leukemia. Enzymes can be applied in chemical analysis and as a research instrument in the life sciences[3].

Bioenzyme as Catalyst:

Enzymes are biocatalysts- the catalysts of life. A catalyst is defined as a substance that increases the haste or rate of a chemical response without itself witnessing any change in the overall process. Enzymes may be defined as biocatalysts synthesized by living cells. They are protein in nature[4]. Biocatalysts is now a leading enabling technology for the perpetration of sustainable chemicals' products not just in fine chemicals and medicinal products but indeed in the product of commodity chemicals and bio-based plastics. Biocatalysts is Green and Sustainable. it is compatible with 10 of the twelve principles of Green Chemistry, the other two being product-design- acquainted rather than process design. Enzymes are biodegradable, biocompatible and sourced from renewable coffers and, thus, directly find their place in bio-based frugality. They avoid the use of noble essence and their precious junking to trace quantities, to veritably low situations, from products. Enzymatic responses are performed under mild conditions – primarily in water at ambient pressure and temperature – and are, thus, lower energy ferocious and have no demand for special outfit. They are veritably chemo- and stereo selective and, thus, yield better quality products. In short, they induce less waste and are greener at lower costs. Also, dramatic improvements in molecular biology and biotechnology, during the last two decades, have made it possible to develop minimally sustainable biocatalytic processes marrying low cost with a low environmental impact. One of the reasons for waste, especially in the product of fine chemicals and medicinal, is the application of stoichiometric, primarily inorganic, reagents in organic condensation. Applicable exemplifications include reductions with essence(Na, Mg, Zn, Fe) and essence hydride reagents($LiAlH_4$, $NaBH_4$) and oxidation with permanganate, manganese dioxide, and chromium(VI) reagents. Mineral acids(H_2SO_4, HF, H_3PO_4) and Lewis acids($AlCl_3$, $ZnCl_2$, BF_3), used as reagents in the response or in downstream processing, are another top source of waste. Likewise, due to the molecular complexity of utmost medicinal, their conflation entails multistep mixtures that are certain to produce further waste than mixtures of further simple commodity chemicals. The remedy for these issues is tone-apparent negotiation of these extravagant stoichiometric practices with further snippet- and step-provident catalytic bones. Compactly put, the secret to green and sustainable chemistry is the employment catalysis: miscellaneous catalysis, homogeneous catalysis, organ catalysis, and biocatalysts in organic condensation[5].

Sustainable Chemistry:

Sustainable chemistry in the department of environmental chemistry of the German Chemical Society(GDC), SC – a more general aspect swinging from GC – was originally introduced at the launch of the 1990s. The provocation behind this approach was a more general aspect coming from the terrain, i.e., end of products' life side, not the confusion side primarily. Roughly at the same period in the 1990s, primarily in Europe, the term SC was by the organization for Economic Cooperation and Development as "sustainable chemistry is a scientific conception that seeks to enhance the effectiveness with which natural coffers are used to serve mortal requirements for chemical products and services. Sustainable chemistry involves the design, product and use of effective, effective, safe and more environmentally benign chemical products and processes. Considering this, SC remains concerned with the products themselves and their manufacture and is veritably near to the twelve principles of GC[6]. SC is defined as a process that provokes invention in all diligence to produce and find new chemicals, manufacturing processes, and product slave boat practices that will deliver lesser performance and lesser value while achieving the objects of guarding and conserving mortal health and the terrain. The rapid-fire and sometimes wild growth of mortal exertion has led to unlooked-for and dynamic relations between the increasing population, food consumption, industrialization, and environmental damages. Specifically, the ecological and health goods of the product, distribution, operation, and release of chemicals on an adding scale in a nearly unrestricted setting have created worldwide concern and led to the establishment of sustainable development[7].

GREEN CHEMISTRY:

Technology that is fast turning out to be a veritably seductive content for academic as well as artificial systems. Green styles within GC generally. Green Chemistry (GC) is an emerging involves replacing dangerous detergents with inoffensive bones so that the ultimate can be incorporated in a specific process. Green logical chemistry (GAC) is the stylish [8]. The terrain is the environment within which all living effects on earth attend to immortalize their actuality. Before the Industrial Revolution, the relationship between mortal beings and the terrain evolved at a fairly harmonious pace. Nevertheless, the growing size of artificial processes upsets this harmony. Addition of population and urbanization has whisked the production of natural coffers, performing in enormous challenges to the commerce between man and nature. Thus, a need has arisen to find results for balancing natural resource use and saving the terrain. In response to these pitfalls, the term" Green Chemistry" came into being with the thing of lowering environmental pollution and creating sustainable backups to artificial chemistry chemicals. Green chemistry focuses on the creation of clean chemical products and processes by reducing the operation and generation of dangerous chemicals. Its main end is to encourage sustainability and save natural resources. It also attempts to avoid the emigration of unsafe chemicals to the terrain, make cheap and less dangerous chemical confusion, and encourage indispensable technologies with minimum detriment on mortal health and terrain [9].

Operations of Green Chemistry GC generalities have been used in colorful operations across much diligence, which include agrochemicals, pharma, as well as accounting wisdom. Exemplifications include.

- Within the pharma assiduity, greener synthetic protocols are being employed to reduce waste and toxin.
- Within the agrochemical assiduity, memoir grounded fungicides and diseases are designed to reduce environmental impacts [10].

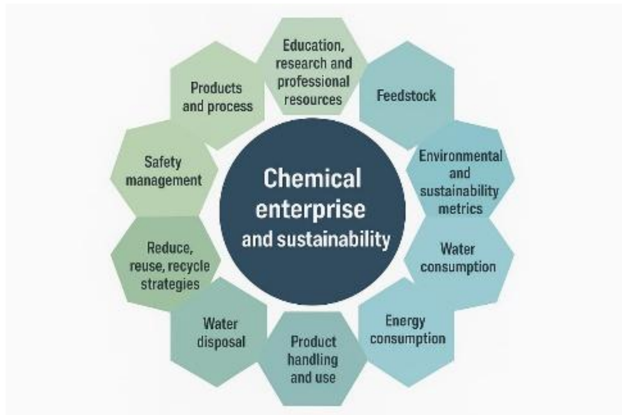

Figure 1: Chemical Enterprise and sustainability.

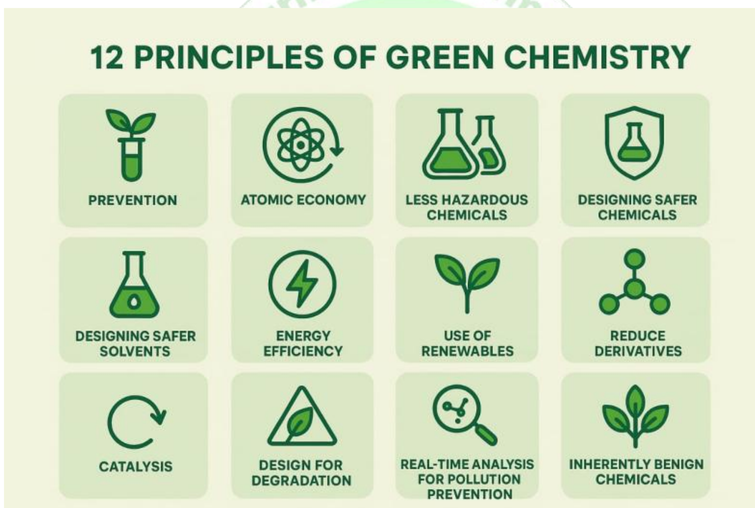

Figure 2: Principle of Green Chemistry.

Recent Research and Innovations:

Nanoenzymes:

Biocatalysts are traditionally defined as realities of natural origin that beget chemical responses, generally under mild conditions (e.g., physiological temperature, pH, ionic strength, and limited substrate attention). Nanozymes, though substantially synthetic, innately retain the capability to beget being or new-to-nature biochemical responses, irrespective of whether their substrates and products match those of enzymes. The development of enzymes for responses that enzymes cannot beget is important, as it could lead to the discovery of new catalytic processes with broad operations in areas where enzymes are limited. Also, enzymes operate efficiently under mild, biologically compatible conditions, in discrepancy to conventional NATO catalysts that bear high energy in puts or concentrated substrates. This positions them as promising campaigners for sustainable operations in environmental remediation, chemical condensation, and energy product. Traditional enzyme mimics are generally constructed to replicate common features within active point of enzymes, including the capability to bind and stabilize response transition countries, convert intermolecular responses of reactants into(mock) intramolecular responses, the Presence of rightly acquainted and located functional groups, and solvation parcels and original pH different from those of the bulk result 50. In contrast, enzymes of ten gypsum structures different from enzymes yet main effective in biocatalytic process. This suggests enzymes aren't the only design for catalyzing biochemical responses and underlines the biocatalytic eventuality of synthetic nanostructures. Although enzymes constructed to recall these enzymatic characteristics of ten exhibition enhanced biocatalytic performance, where recommended That a nanoscale perspective shall be placed on understanding the processes being at the active point of enzyme during the chemical

Transformation of the substrate, which may partake some enzyme-suchlike parcels but also may involve it unique mechanisms. Enzymes are defined by their nanoscale infrastructures, which give spatially confined interfaces to interact with substrates. Distinguish them from ionic catalysts (e.g., Fenton reagents) and traditional small-patch enzyme mimics[11].

Immobilization:

Utmost of the enzymes are of high cost; they must be employed efficiently, and their capability to execute the same function multiple times is regarded as a precious asset. As both enzyme and product are dissolved, separation becomes complex and therefore precious. Some of the enzymes applied in efficiency are veritably expensive, so the enzymatic process will be provident and useful only if these can be reused. The immobilization entails the metamorphosis of to a solid catalyst form of water-answerable enzyme, which allows the separation, hence immobilization styles should be embraced as a strong tool to use in processes. Biocatalysts grounded on enzymes have been investigated for decades due to their catalytic power, their high degree of particularity, and stereo selectivity. These parcels allow enzymes to beget responses witnessing in milder conditions, such as low temperature and pressure, turning them into intriguing campaigners for several artificial operations[12].

Physical Adsorption:

Physical adsorption is the one of the simplest styles employed for immobilization in accuracy. Physical adsorption is an affordable and easy system, which maintains high catalytic exertion; therefore, it is employed more frequently than other procedures. This system also permits the exercise of expensive support equipment; accordingly, this reusability of the support material provides beneficial advantages for artificial products. In discrepancy, this system does not give high stability and may lead to loss of biomolecules that's paralyzed upon washing and operation.

Entrapment and Encapsulation:

Encapsulation and ruse the encapsulation process is grounded on the ruse of the biomolecule in a polymeric matrix. The main advantage of this fashion is that it allows the transport of low molecular weight (LMW) composites through the passable matrix. Entrapment matrix is generally formed during the immobilization process. Thus, the parcels of the gel matrix and the conditions used for the encapsulation should be compatible with the enzyme to be paralyzed. Among the immobilization styles applicable to plant cells, the most common and effective styles are ruse or encapsulation of cells within a gel or in a solid support.

Covalent Bond:

Covalent list results in a strong list so the biomolecule to be paralyzed doesn't come off from supports during use. Due to this close commerce between enzyme molecules and supports, there is great heat stability. Still, this commerce, sorrowfully, doesn't enable the paralyzed enzyme molecules to move freely and therefore reduce the enzyme exertion. Enzymes paralyzed using this system also can readily come into contact with substrates as the enzymes are fixed on the face of the support material. This system is less effective for cell immobilization, and support equipment isn't-renewable.

Cross Linking System:

Cross-linking is an immobilization fashion that combines both covalent cling and ruse. Immobilization by this system requires cross-linking agents such as glyceraldehyde and bisisodiacetamide. The enzyme exertion of paralyzed medications cross-linked with these reagents is dependent upon the degree of cross-linking[13].

Metagenomics:

The word metagenomics refers both to a branch of scientific inquiry and to a collection of methods that allow culture independent examination of a microbial assemblage in any environmental sample. It is a facilitation for probing the gene-rich reservoirs of uncloned microbiota, directly without employing traditional culturing techniques, and is founded on the principle of direct DNA isolation from a complex environmental sample having a variety of microbiota; to expose the actual microbial makeup of the environment. It was initially used by Handelsman and his colleagues in 1998; when cloning the metagenome of an environmental soil sample to gain access to the combined genomes and biosynthetic apparatus of the microbial microflora. Metagenomics emerged as one of the hottest research areas for microbial ecology in the past decade. Beginning From 16S rRNA marker gene analysis for determining the compositions of communities to whole metagenome shotgun sequencing, which in turn enables functional analysis and metagenomics applications across a broad range of research fields. The minimized cost of the rising amount of data, with the advent of next-generation sequencing, revealed considerably increasing requirements for bioinformatic tools in metagenomics Over the last few years, biocatalysis has emerged as a sustainable alternative to conventional chemistry in the chemical and pharmaceutical industries.[14] The benefits of biocatalysis are that reactions take place in aqueous solvents under mild conditions, and the resultant high region- and enantio-selectivity without any tedious purification processes[15]. As a result of economic and environmental benefits combined with the imperative need to establish sustainable production processes for chemical manufacture, use of the biocatalysts in industry is gaining wide acceptance today. Several companies have started to make commitments to the United Nations' Sustainability Goals, seeking to achieve numerous of the 17 goals established by the United Nations. In spite of this nascent shift in economic culture, the establishment of effective bioprocesses continues to face a number of hurdles to become an even more widely used technology that surpasses traditional chemical production processes in respect to efficiency, productivity, and environmental impact[16].

Future Prospective:

Waste Water:

With the onset of fast population growth in the world, the problem of treatment of sewage and artificial waste has only grown more burning. Moment, close to 70–80 of gutters and aqueducts have come weakened with wastes, causing serious hazards to mortal health and the terrain. Industrialization, posterior urbanization, and ever adding population constantly pollute the abecedarian requirements of actuality, similar to land, air, and water. Artificial conditioning significantly contributes to environmental pollution (Kumar et al., 2020). These artificial zones primarily emit effluent, which contains heavy essences such as Zn, Ni, Cr, Pb, Cu, Cd, and Hg, along with organic composites like phenols and formaldehyde. In ecosystems, the biomagnification of heavy essence poses a significant threat to mortal health. Backwaters released from this diligence frequently contain dangerous heavy essence such as zinc (Zn), nickel (Ni), chromium (Cr), lead (Pb), bobby (Cu), cadmium (Cd), and mercury (Hg), as well as organic composites like phenols and formaldehyde. The biomagnification of this heavy essence in ecosystems poses significant pitfalls to mortal health and the terrain, challenging the perpetration of effective wastewater treatment processes to alleviate these impacts [17].

Treatment of Bioenzymes:

The sample of effluent was treated with 1, 5, 6, and 10 attention to bio enzymes. There were 12 teacups filled with effluent samples and enzyme results deduced from citrus fruit peels turmoil at 1,5, 6, and 10 attention under static conditions. The selection of bio enzymes attention was typically dependent on the trade-off between effectiveness, cost-effectiveness, safety, and earlier studies. They were also anatomized for physicochemical and heavy essence content from the 0th day over to the 20th day. A control was also contemporaneously run along with to compare the effluent reduction with the bio enzymes treated samples [18].

Use of Bioinfirmatic and Ai in Enzyme Design:

It is a universal approach to profit from enzymes in extreme environments and to leverage their mechanism of adaptation to the environment. Most semi-rational approaches reveal the mechanism of enzyme catalytic stability by comparing and analyzing biological enzymes in extreme and regular environments. Yet, the same amino acid may be different or even opposite in various positions or enzymes, which can limit the predictive power of prediction models. Due to these issues, the AI prediction model will be drawn nearer towards the average value, nullifying the predictive value of outlier samples and the weight of influence of amino acids in the model. Enzyme design has evolved a path from randomly driven irrational design, to empirically driven semi-rational design, to computationally driven rational design. With the advancements sequencing technology, high-performance computing hardware and AI algorithms, modeling and analysis of complex biological systems have been greatly optimized. Modeling to predict or generate molecules in biological systems that increasingly performs better. This hastened the advancement of existent enzyme molecular design strategies towards algorithmic and data-driven design. Accumulation of spontaneous mutations is unguided. Mutations are randomly introduced at any position in a protein structure to generate diversity. Hotspots/mutations that could be important for stability are selected by bioinformatics as templates to generate focused random libraries. Visual expert analysis of bioinformatic data to manually predict a few potential stabilizing substitutions. Bioinformatic analysis of natural mutation patterns to identify a limited set of hotspots/mutations Variants created by swappingamino acid observed in related natural sequences [19].

Classification of different strategies to design more stable enzyme

1. Natural evolution
2. Stochastic approaches
3. Empirical rational design
4. Systematic rational design
5. Chimeric approaches [20].

CONCLUSION:

Biocatalysts provides an efficient, sustainable alternative to conventional chemical processes. Enzymes' natural specificity, biodegradability, and ability to function under mild conditions significantly reduce energy requirements, waste generation, and environmental impact. Innovations such as enzyme engineering, immobilization, metagenomics, and AI-driven design continue to expand their industrial potential, from pharmaceuticals to wastewater treatment. As industries align with global sustainability goals, the integration of bio enzymes as catalysts is poised to become a cornerstone of green and sustainable chemistry, driving cleaner production methods and contributing to a circular, bio-based economy.

ACKNOWLEDGEMENT:

This work highlights the transformative role of bio enzymes as catalysts—a cornerstone in advancing sustainable chemistry for modern industrial and environmental applications. The authors—Ms. Samiksha Ghuge, Dr. Rahul Khaire, Ms. Ankita Kathale, Ms. Lochani Sankhe, Ms. Tejaswini Bhandare, and Ms. Payal Korade from Pravara Rural Education Society's College of Pharmacy (For Women), Chincholi, Nashik—provide a comprehensive outlook on how bioenzymes, through their high specificity, biodegradability, and eco-friendly action, can replace conventional chemical reagents and promote green chemistry. This perspective emphasizes the integration of enzyme engineering, immobilization, and bioinformatics-driven innovation as highly dynamic and technology-driven strategies. It promises a more sustainable, efficient, and accurate system that not only addresses industrial and pharmaceutical needs but also contributes to global environmental health, ensuring a safer and greener future for chemical practices.

REFERENCE:

1. Alca'ntara AR, Domínguez de María P, Littlechild JA, Schürmann M, Sheldon RA, Wohlgemuth R. Biocatalysis as key to sustainable industrial chemistry. ChemSusChem. 2022;15(9): e202102709.
2. Khan A. Biocatalysts and enzyme engineering: pioneering green chemical transformations. Front Chem Mater Catal. 2024;1(1):88-105.
3. Sheldon RA. Green chemistry and biocatalysis: engineering a sustainable future. Catal Today. 2024; 431:114571.
4. Satyanarayana U, Chakrapani U. Biochemistry. 3rd ed. Kolkata: Arunabha Sen; 2006.

5. Sheldon RA, Woodley JM. Role of biocatalysis in sustainable chemistry. Chem Rev. 2018;118(2):801-38.
6. Zuin VG, Eilks I, Elschami M, Kümmerer K. Education in green chemistry and in sustainable chemistry: perspectives towards sustainability. Green Chem. 2021;23(4):1594-608.
7. Horváth IT. Introduction: sustainable chemistry. Chem Rev. 2018;118(2):369-71.
8. Venkatesan K, Sundarababu J, Anandan SS. The recent developments of green and sustainable chemistry in multidimensional way: current trends and challenges. Green Chem Lett Rev. 2024;17(1):2312848.
9. Kurul F, Doruk B, Topkaya SN. Principles of green chemistry: building a sustainable future. Discov Chem. 2025;2(1):68.
10. Bhaskar S, Kishore V. Advancing green and sustainable chemistry: importance and applications in human life.
11. Zhang R, Yan X, Gao L, Fan K. Nanozymes expanding the boundaries of biocatalysis. Nat Commun. 2025;16(1):6817.
12. Santos S, Puna J, Gomes J. A review on bio-based catalysts (immobilized enzymes) used for biodiesel production. Energies. 2020;13(11):3013
13. 13.Eş I, Vieira JDG, Amaral AC. Principles, techniques, and applications of biocatalyst immobilization for industrial application. Appl Microbiol Biotechnol. 2015;99(5):2065-82.
14. Sulaiman S, Baeshen M, Abdelkader HS. Metagenomic and metabolomic technologies: species identification & discovery of novel biocatalysts from marine organisms. Int J Novel Res Life Sci. 2021;8:5-16.
15. Hogg BN, Schnepel C, Finnigan JD, Charnock SJ, Hayes MA, Turner NJ. The impact of metagenomics on biocatalysis. Angew Chem Int Ed. 2024;63(21): e202402316.
16. Guazzaroni ME, Silva-Rocha R, Ward RJ. Synthetic biology approaches to improve biocatalyst identification in metagenomic library screening. Microb Biotechnol. 2015;8(1):52-64.
17. Geetha NB, Rajagopal M, Priya S, Rajmohan K. Sustainable sullage water treatment using bioenzymes: an experimental perspective. Int J Environ Sci. 2025;11(2s):567-76.
18. Natt SK, Katyal P, Phutela UG, Chandel S. Bioremediation of electroplating industrial wastewater using bioenzymes generated from citrus. Environ Conserv J. 2025;26(1):1-8.
19. Ming Y, Wang W, Yin R, Zeng M, Tang L, Tang S, et al. A review of enzyme design in catalytic stability by artificial intelligence. Brief Bioinform. 2023;24(3):bbad065.
20. Suplatov D, Voevodin V, Švedas V. Robust enzyme design: bioinformatic tools for improved protein stability. Biotechnol J. 2015;10(3):344-55.