BIO-CATALYSIS: A BRIEF REVIEW

Abstract

There are a number of chemical transformations that are based on bio catalysis that are among the oldest known to humans. Biocatalysis involves performing chemical reactions on organic compounds through the use of natural catalysts, such as protein enzymes. As part of this task, both enzymes that have been isolated to a greater or lesser extent and enzymes that are still residing inside living cells are utilized. Traditionally, bio catalysis has been used to convert non-natural chemical compounds into natural organic compounds, with biological catalysts being employed as a catalyst to the chemical processing of man-made organic compounds. However, in the past 30 years, bio catalysis has been widely applied to the production of fine chemicals, especially in the pharmaceutical industry. Here, the author emphasizes on the different applications of biocatalysts that can be applied in the pharmaceutical industry, highlighting their utility.

Keywords— Bio catalysis, Enzyme, Enzyme synthesis, Catalyst, pharmaceutical industry.

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I. INTRODUCTION

In chemical catalysis, natural catalysts, such as enzymes from proteins, are used to carry out chemical transformations on organic compounds by using natural enzymes as catalysts. Enzymes are available in two types: those isolated from living cells or those living inside living cells.[1]

1. **Advantages of bio catalysis***:* It is essential that organic synthesis is characterized by selectivity in order to obtain high yields of a specific product. The most common synthetic needs can be met using a wide range of selective organic reactions. Although chiral synthesis has made significant progress in recent years, organic chemists are still experiencing problems when it comes to chirality.[2]

2. **Enzymes display three major types of selectivity's:** The concept of chemo selectivity is based on a single type of functional group being acted on by enzymes, which means that other sensitive functional groups, which would normally be destroyed under chemical catalysis, are preserved. The result is cleaner biocatalytic reactions, and laborious purification of impurities produced by side reactions becomes much easier.[3] Through the complex three-dimensional structure of enzymes, enzymes are capable of separating functional groups located at different locations within a substrate molecule.

3. **Enantioselectivity:** As enzymes have L-amino acids as their building blocks, enzymes are chiral catalysts, since they contain amino acids. As a result, the enzyme-substrate complex will be able to identify chirality of the substrate molecule. Enantiomers of prochiral substrates may react differently with their counterparts, and enantiomers of racemic substrates may react differently with their counterparts.[4]

   Especially this last reason is one of the reasons synthetic chemists have become interested in biocatalysis over the past few years. Agrochemicals and drugs rely heavily on chiral building blocks, so this interest is driven by the need to synthesize enantiopure compounds. In addition, biocatalysts exhibit the advantage of being environmental friendly, as they are able to degrade completely. Furthermore, enzymes are able to produce a wide range of compounds under mild conditions, which minimizes undesirable side reactions, such as decomposition, racemization, and rearrangement.[5]

4. **Literature survey**

- **Stabilization of proteins using natural methods:** *Biocatalysts with a temperature range:* By studying their biochemical properties and three-dimensional structures, the authors explored how nature stabilizes proteins. Experiments at Exeter have been conducted on several different types of enzymes to illustrate this point. Y-lactamase, dehalogenase, amino acylase, pyro glutamyl carboxypeptidase, lysophospholipase, and alcohol dehydrogenase were all used. A robust biocatalyst based on enzymes found in thermophilic and hyper thermophilic organisms is being developed for fine chemicals and pharmaceuticals. Their increased stability is essential to these industries because they are frequently required for commercial reactions. [6-7]

- **Protein motions in centisecond range are correlated with biocatalyst activity in non-aqueous environments:** In the aqueous phase, enzyme catalysis and protein dynamics exhibit a strong correlation, according to studies. In non-aqueous environments where proteins exhibit great ranges of motion depending on the solvent, the effects of protein dynamics on enzyme activity can be studied to an extent not possible in aqueous environments. As part of the experiments, we conducted using heterolyophilized subtilisin Carlsberg, we treated it with inorganic salts and suspended it in organic solvents to perform variable-temperature kinetics and X-band electron spin resonance spectroscopy. The salt activation of organic solvent-dependent biocatalyst preparations increases transition-state flexibility, resulting in a higher S†. In contrast, H† was negligible regardless of salt type or salt content. A number of enzyme activators, including 4-fluorobenzenesulfonylfluoride and 4-ethoxyfluorophosphinyloxy-TEMPO, had no significant effect on 19F chemical shift measurements or hyperfine tensor measurements. [8-9]

- **Cytochrome C as a biocatalyst:** Researchers have demonstrated in the present study that electron-transporting Type-c cytochromes are also capable of catalyzing peroxidase-like reactions with hydrogen peroxide or organic hydroperoxides as electron acceptors. A review of the catalytic activity of cytochrome c has been conducted based on site-directed mutagenesis and chemical modification.[10]

- **A site-directed mutation enhances the biocatalytic efficiency of polycyclic hydrocarbon oxidation by iso-1-cytochrome C:** Polycyclic aromatic hydrocarbons (PAHs) are oxidized by iso-1-Cytochrome c when hydrogen peroxide is present. Pyrene and anthracene are oxidized by yeast cytochrome c to form anthraquinone and 1,8-pyrenedione. Site-directed mutations were performed on Cys102 and Phe82 of Saccharomyces cerevisiae iso-1-cytochrome c. Of these two modifications, Phe82 had significantly more effect on its kinetic behavior than Cys102. In comparison with wild-type iso-1-cytochrome c, it displayed 10 times the catalytic efficiency. As a result, Phe82 variants shrank more rapidly when hydrogen peroxide was added. The hemoprotein stability or activity did not change significantly with increasing tetrahydrofuran concentrations. [11-12]

- **A de novo biocatalyst design is as follows***:* De novo enzyme design has produced proteins with impressive catalytic efficiency. In many reactions, there are no efficient enzymes that can be designed with the current methods.[13]

- **Activated biocatalysts for alpha-ketoacid decarboxylation based on thiamine intermediates immobilized on silica surfaces:** Two phosphate-immobilized 'active aldehydes' of thiamine catalysis were used in this study. In the present study, bio-composites were evaluated as catalysts for decarboxylation of pyruvate and benzoyl-formate, regardless of whether or not aldehyde additives were added.oduction of 2-hydroxyalpha-ketones, acetoine, and benzoin, they are very stable and extremely effective catalysts.[14]

- **A new approach to fluorinated biocatalysts in organic media: solubilization of cytochrome C in organic media containing fluoroalkyl end-capped N-(1,1-dimethyl-3-oxobutyl) acrylamide oligomer:** It is possible to solubilize cytochrome c

in methanol with fluoroalkyl end-capped N-(1,1-dimethyl-3-oxobutyl) acrylamide oligomers, but not with the non-fluorinated counterparts. Using non-aqueous methanol to oxidize pinacyanol chloride with hydrogen peroxide, the fluorinated oligomer–cytochrome C aggregate performed well as a fluorinated biocatalyst.[15]

- **Hydantoinase enzymes are useful as catalysts for synthesis of unnatural chiral amino acids:** Using hydantoinase technology, the authors suggest that unnatural chiral amino acids could be produced, which could be used as pharmaceutical components in the future.[16]

- **The role of lipases as practical biocatalysts:** There is exciting potential for more practical applications of lipases in organic synthesis resulting from new research on lipases, those ubiquitous enzymes used in a wide range of industrial processes.[17]

- **Metagenomic analysis, gene discovery, and the deal biocatalyst:** By this method, optimal conditions for biotransformation processes can be determined without regard to the properties of the biocatalysts. These technologies can be used to identify the 'ideal biocatalyst' for the process. A biocatalyst is identified through the discovery of genes and the evolution of enzymes. It is necessary to introduce a technology that circumvents microbial culturability in order to facilitate in vitro evolution. A number of technologies are currently available for screening metagenomic libraries, amplification of genes, or even sequencing the whole genome, providing access to volumes of sequence data that are not accessible by traditional screening methods. [18-19]

- **Biocatalysis- Biological systems for the reduction of chemicals:** Biocatalysis uses enzymes' catalytic potential to produce pharmaceutical and chemical building blocks and end products. Through biotransformation processes, organic compounds can be transformed into functionalized products by combining fermentation with petrol-based chemistry. [20]

- **In the bioconversion process of cephalosporin C, Vitreoscilla hemoglobin fusion protein enhances activity and stability of D-amino acid oxidase:** Rhodotorula gracilis D-amino acid oxidase (DAO) was fused with Vitreoscilla hemoglobin (VHb) to determine whether bacterial hemoglobin can oxygenate immobilized flavoenzymes. Chemeric enzymes significantly enhanced the bioconversion of cephalosporin C. VHb[1]DAO immobilized on a surface showed a 12.5-fold higher catalytic efficiency and threefold higher operational stability than DAO immobilized on a surface. Within 60 minutes, 120 mM cephalosporin C was bioconverted by immobilized VHb-DAO (2500 U/L). It was possible to maintain 90% of the initial activity of immobilized VHb-DAO without additional H2O2 or flavin adenine dinucleotide (FAD) after 50 cycles of enzyme reaction. The purity of glutaryl-7- aminocephalosporanic acid according to HPLC analysis is 99.77%. When compared with immobilized DAO, VHb[1]DAO has a twofold increase in relative specificity. It is possible that cephalosporin C may be more effective as a result of a conformational modification of the VHb-DAO fusion protein. [21-23]

- **Developing an ideal biocatalyst:** In fine chemicals and pharmaceutical manufacturing, enzymes have enormous potential as biocatalysts, but their application is often limited by evolution-driven characteristics. Informed selection and mutation can produce designer biocatalysts through recombinant DNA technology. Nevertheless, tailoring catalyst properties to be optimal for both a given reaction and the industrial processes that the enzyme will be employed in is essential for fully realizing the potential of designer enzymes in industrial applications.[24]

- **A new generation of biocatalysts for clean industrial products and processes:** Natural and engineered biocatalysts that can be customized for clean industrial applications have been discovered through biodiversity discoveries, molecular biology, and computational science.[25]

- **Development of protein oxygenases for biocatalysis: A** complex, unstable, and low-catalytic rate oxygenase enzyme has limited practical applications. Engineers have relied on oxygenases for their ability to perform complex chemistry in a highly selective and specific manner. Increasing understanding of oxygenases' structure-function relationships makes them increasingly useful in chemical synthesis and bioremediation.[26]

- **Choosing mutations that enhance protein stability:** Various methods can be used for selecting mutations that increase protein stability, such as rational design, functional screening, and comparison with naturally occurring homologous proteins. An increasing number of examples of stable proteins are emerging, and they are becoming easier to engineer. It is not standard practice to select thermostable mutations. Thermal inactivation complicates the selection process for proteins because they employ many structural tricks to achieve stability.[27]

- **A new biocatalyst for the resolution and synthesis of (S)-1-(2-naphthalyl) ethanol using pea protein:** The authors synthesized (R, S) 2-naphthyl ethanol (> 99% ee, yield; about 50%) by immobilizing pea protein (IPP) to yield 2-acetonaphthone by selective oxidation of the (R)-enantiomer. Optical purity and yield do not suffer if IPP is reused at least three times consecutively.[28]

- **Xylose reductase in Candida tenuis was identified as a highly selective biocatalyst for the production of aromatic alpha-hydroxy esters, and its efficiency was improved by protein engineering: In** this study, two Trp-23 mutants of Candida tenuis xylose reductase are shown to catalyze the reduction of homologous aromatic alpha-keto esters with absolute pseudore-face stereoselectivity, producing high R-alcohol yields.[29]

- **Mucin 1 is produced by repetitive fusion protein cleavage using immobilized bovine enterokinase: In** mammals' metabolism, enterokinase hydrolyzes peptide bonds. As a highly specific amino acid sequence (Asp)(4)-Lys can be cleaved by this enzyme, it can be used to cleave fusion proteins. In CHO cells, the recombinant fusion protein mucin 1 is produced, and it may be used to treat cancer adaptively. We demonstrate that immobilized enterokinase can cleave mucin fusion proteins for the first time. Immobilizing the biocatalyst allows for a facile biocatalytic reaction due to

the separation of the catalyst and target protein. An immobilized enterokinase solution was applied 18 times in total. A 419-fold increase in enzyme utilization (total turnover number) was achieved through both immobilization and process optimization. In order to compensate for slight enzyme inactivation during the reaction cycle, the process time was adjusted. This resulted in the complete cleavage of fusion proteins. Their purification process was simple and efficient, and they were able to isolate mucin 1 with over 90% purity. The present study demonstrated that enterokinase is an attractive tool for cleaving fusion proteins. [30-34]

- **A unique biocatalyst based on polymeric nanofibers carrying enzymes:** Bioactive nanofibers are used by the authors to demonstrate how materials engineering can enhance the efficiency of enzyme immobilization. A typical PS nanofiber diameter of 120 nm was prepared and tested for its catalytic efficiency in biotransformations. A functionalized PS was chemically attached to R-chymotrypsin and electrospun into nanofibers. As a result of a titration of the active site, enzyme loadings up to 1.4% (wt/wt) were determined, which is equivalent to a surface monolayer coverage of over 27.4%. It was also found that nanofibrous R-chymotrypsin was significantly more active in non-aqueous conditions than its native counterpart in organic solutions. Additionally, the covalent binding enhanced the enzyme's resistance to structural denaturation in methanol, resulting in an 18-fold longer half-life than the native enzyme. [35-38]

- **Non-Aqueous Biocatalysis in Heterogeneous Solvent Systems:** For the production of compounds with applications in food, feed, chemicals, and pharmaceuticals, biocatalysis has become a useful alternative to chemical processes. Nevertheless, achieving desired rates, yields and selectivity of the reaction is not necessarily an easy task. Using non-conventional media, such as non-aqueous heterogeneous systems, can optimize biocatalyst performance. A focus is placed on reverse micelles, supercritical fluids, and ionic liquids in this article, which discusses some current trends in biocatalysis.[39]

- **The synthesis of new electronic materials and photovoltaics using biocatalysis:** Using hematin as a biocatalyst, ruthenium complex-based macrodye and dinuclear complex were synthesized. In comparison with polymeric complexes, dinuclear complexes have a photovoltaic overall efficiency of 2.1%. A novel pegylated polyphenolic synthesis methodology has also been developed that is environmentally friendly. We conducted the reactions in aqueous media without using organic solvents. The properties of the synthesized polymers can be further tailored by solubilizing them in organic or aqueous solutions. Additionally, we describe a biomimetic method for synthesizing polypyrrole and thiophene substitutes with polyelectrolytes like polystyrene sulfonate (SPS). With the help of a synthetic enzyme based on hematin, Pyrole (PYR) and 3,4-ethylene di-oxy thiophene (EDOT) were polymerized. Additionally, copolymers of EDOT and PYR exhibit high electrical conductivity. [40-42]

- **Cutinase structure, function and biocatalytic applications: S**everal biotechnological applications may be possible for natural cutinases. It has been successfully cloned and expressed cutinases from Fusarium solani f. Fusarium solani

in Escherichia coli as well as Saccharomyces cerevisiae. It is also discussed and compared with other lipases on how this cutinase functions as a lipase in three dimensions. As well as the preparation of various cutinase forms and the media in which enzymatic reactions occur, including hydrolysis, esterification, transesterification, and resolution of racemic mixtures, this article discusses biocatalytic applications of cutinase. Especially in anionic reversed micelles, hexanol serves as a substrate, co-surfactant, and stabilizing agent for cutinase preparations. In addition, the article discusses the development of processes based on the operation of cutinase reactors. [43-44]

- **Biocatalytic hydrolysis of oxiranes via epoxide hydrolases from bacteria: enantioconvergent process:** We were able to hydrolyze 2-3-disubstituted oxiranes to form vicinal diols using various bacterial strains with epoxide hydrolase activity in as much as 97% efficiency at 100% conversion by using various bacterial strains with epoxide hydrolase activity. 18OH2-labelling experiments were conducted using partially purified Nocardia EH1 epoxide hydrolase to determine the mechanism of deracemization. By attacking the carbon atom of the (S)-configured oxirane with OH2, the reaction proceeds concomitantly. [45]

- **Biological Polymers: Structure and Catalytic Mechanisms of Hydroxynitrile Lyases:** Alpha-cyanohydrins can be converted into aldehydes or ketones by hydroxynitrile lyases, which catalyze reversible conversions. Additionally, these enzymes can be used in industrial biocatalysis to enantioselectively condense HCN with aldehydes and ketones. Hydroxynitrile lyases (HNLs) have evolved from a variety of ancestral proteins through convergence evolution. To understand the mechanism of the reaction, molecular modeling, enzyme kinetics, spectroscopy, and structural data were used. All of the HNL reactions are thought to be catalyzed by acid-There is an amino acid residue from the catalytic triad that serves as a general acid or base in beta-hydrolases, whereas a histidine residue provides the same function in FAD-deThe catalysis mechanism of carboxypeptidases is similar There have been several mechanistic proposals that have proposed that the active site has a positive electrostatic potential that is catalytically relevantnt by several mechanistic proposals. [46-48]

II. MODEL DEVELOPMENT FOR FERMENTATION AND BIOCATALYSIS PROCESS

Raw material costs are typically high in fermentation or biocatalysis production processes. Optimizing strains and processes is therefore crucial to success. It is possible to optimize a microorganism or biocatalyst by understanding its physiology and mechanism. Models can be developed to simulate the behavior of bioprocesses based on this knowledge. Modeling the process dynamics around the rate-limiting process, which is usually an enzymatic reaction, is a popular modeling strategy. The rates are dependent on both the concentrations of substrates and inhibitors, as well as the concentrations of enzymes. [49-51]

Using Michelis-Menten type kinetic forms coupled with cybernetic principles, successful models have been developed recently. Based on the kinetic form, the substrate concentration is accounted for, as well as the catabolite repression of substrates and the rate

limiting effects of substrates. Alternatively, cybernetic principles simulate the dynamics of enzyme concentration profiles, which may be determined by some kind of optimization criteria. An industrially relevant bioprocess will be used in this workshop to illustrate modeling strategies. A model can be presented for any bioprocess, but the strategy can be applied to any process. [52-53]

III. CONCLUSION

There have been a number of reviews published on the topic of protein stabilization, using cytochrome c as a biocatalyst, creating new biocatalysts, applying biocatalysts to clean industrial products, and using biocatalysts for industrial processes. As the name suggests, biocatalysis is the process of performing chemical reactions on organic compounds by using natural catalysts, such as enzymes found in proteins. This task is accomplished either by working with enzymes that have been isolated or with enzymes that are residing inside living cells that have been isolated. The biocatalytic activity of iso-1-cytochrome c can be improved by site-directed mutagenesis in the oxidation of polycyclic hydrocarbons by iso-1-cytochrome c. Consequently, the various biocatalysts are used in different reactions to give a predominant product with a high yield, a short reaction time and an environmentally friendly reaction. [54-55]

REFERENCES

[1] Bell EL, Finnigan W, France SP, Green AP, Hayes MA, Hepworth LJ, Lovelock SL, Niikura H, Osuna S, Romero E, Ryan KS. Biocatalysis. Nature Reviews Methods Primers. 2021 Jun 24;1(1):1-21.
[2] Yi, D., Bayer, T., Badenhorst, C. P., Wu, S., Doerr, M., Höhne, M., & Bornscheuer, U. T. (2021). Recent trends in biocatalysis. *Chemical Society Reviews*, *50*(14), 8003-8049.
[3] IPyser, J. B., Chakrabarty, S., Romero, E. O., & Narayan, A. R. (2021). State-of-the-art biocatalysis. *ACS Central Science*, *7*(7), 1105-1116.
[4] Guarneri, A., van Berkel, W. J., & Paul, C. E. (2019). Alternative coenzymes for biocatalysis. *Current opinion in biotechnology*, *60*, 63-71.
[5] Winkler, C. K., Schrittwieser, J. H., & Kroutil, W. (2021). Power of biocatalysis for organic synthesis. *ACS central science*, *7*(1), 55-71.
[6] Wu, S., Snajdrova, R., Moore, J. C., Baldenius, K., & Bornscheuer, U. T. (2021). Biocatalysis: enzymatic synthesis for industrial applications. *Angewandte Chemie International Edition*, *60*(1), 88-119.
[7] Schmermund, L., Jurkaš, V., Özgen, F. F., Barone, G. D., Büchsenschütz, H. C., Winkler, C. K., ... & Kroutil, W. (2019). Photo-biocatalysis: biotransformations in the presence of light. *ACS Catalysis*, *9*(5), 4115-4144.
[8] Fryszkowska, A., & Devine, P. N. (2020). Biocatalysis in drug discovery and development. *Current Opinion in Chemical Biology*, *55*, 151-160.
[9] Woodley, J. M. (2020). New frontiers in biocatalysis for sustainable synthesis. *Current Opinion in Green and Sustainable Chemistry*, *21*, 22-26.
[10] Benítez-Mateos, A. I., Contente, M. L., Padrosa, D. R., & Paradisi, F. (2021). Flow biocatalysis 101: design, development and applications. *Reaction chemistry & engineering*, *6*(4), 599-611.
[11] Huang, X., Cao, M., & Zhao, H. (2020). Integrating biocatalysis with chemocatalysis for selective transformations. *Current Opinion in Chemical Biology*, *55*, 161-170.
[12] Sheldon, R. A., & Brady, D. (2021). Streamlining design, engineering, and applications of enzymes for sustainable biocatalysis. *ACS Sustainable Chemistry & Engineering*, *9*(24), 8032-8052.

[13] Sandoval, B. A., & Hyster, T. K. (2020). Emerging strategies for expanding the toolbox of enzymes in biocatalysis. *Current Opinion in Chemical Biology*, *55*, 45-51.
[14] Sheldon, R. A., & Brady, D. (2019). Broadening the scope of biocatalysis in sustainable organic synthesis. *ChemSusChem*, *12*(13), 2859-2881.
[15] Romero-Fernández, M., & Paradisi, F. (2020). Protein immobilization technology for flow biocatalysis. *Current opinion in chemical biology*, *55*, 1-8.
[16] Sheldon, R. A., Brady, D., & Bode, M. L. (2020). The Hitchhiker's guide to biocatalysis: recent advances in the use of enzymes in organic synthesis. *Chemical science*, *11*(10), 2587-2605.
[17] Burek, B. O., Bormann, S., Hollmann, F., Bloh, J. Z., & Holtmann, D. (2019). Hydrogen peroxide driven biocatalysis. *Green Chemistry*, *21*(12), 3232-3249.
[18] Cestellos-Blanco, S., Zhang, H., Kim, J. M., Shen, Y. X., & Yang, P. (2020). Photosynthetic semiconductor biohybrids for solar-driven biocatalysis. *Nature Catalysis*, *3*(3), 245-255.
[19] Hanefeld, U., Hollmann, F., & Paul, C. E. (2022). Biocatalysis making waves in organic chemistry. *Chemical Society Reviews*.
[20] Wu, L., Maglangit, F., & Deng, H. (2020). Fluorine biocatalysis. *Current Opinion in Chemical Biology*, *55*, 119-126.
[21] Alonso, S., Santiago, G., Cea-Rama, I., Fernandez-Lopez, L., Coscolín, C., Modregger, J., ... & Ferrer, M. (2020). Genetically engineered proteins with two active sites for enhanced biocatalysis and synergistic chemo-and biocatalysis. *Nature Catalysis*, *3*(3), 319-328.
[22] Abdelraheem, E. M., Busch, H., Hanefeld, U., & Tonin, F. (2019). Biocatalysis explained: from pharmaceutical to bulk chemical production. *Reaction Chemistry & Engineering*, *4*(11), 1878-1894.
[23] de María, P. D. (2021). Biocatalysis, sustainability, and industrial applications: Show me the metrics. *Current Opinion in Green and Sustainable Chemistry*, *31*, 100514.
[24] Wu, Y., Xu, W., Jiao, L., Gu, W., Du, D., Hu, L., ... & Zhu, C. (2022). Nanobiocatalysis: a materials science road to biocatalysis. *Chemical Society Reviews*.
[25] Seel, C. J., & Gulder, T. (2019). Biocatalysis fueled by light: on the versatile combination of photocatalysis and enzymes. *ChemBioChem*, *20*(15), 1871-1897.
[26] De Santis, P., Meyer, L. E., & Kara, S. (2020). The rise of continuous flow biocatalysis–fundamentals, very recent developments and future perspectives. *Reaction Chemistry & Engineering*, *5*(12), 2155-2184.
[27] Cao, Y., Li, X., & Ge, J. (2021). Enzyme catalyst engineering toward the integration of biocatalysis and chemocatalysis. *Trends in Biotechnology*, *39*(11), 1173-1183.
[28] Marsden, S. R., Mestrom, L., McMillan, D. G., & Hanefeld, U. (2020). Thermodynamically and kinetically controlled reactions in biocatalysis–from concepts to perspectives. *ChemCatChem*, *12*(2), 426-437.
[29] Pérez- Venegas, M., & Juaristi, E. (2021). Mechanoenzymology: State of the art and challenges towards highly sustainable biocatalysis. *ChemSusChem*, *14*(13), 2682-2688.
[30] Xu, K., Chen, X., Zheng, R., & Zheng, Y. (2020). Immobilization of multi-enzymes on support materials for efficient biocatalysis. *Frontiers in Bioengineering and Biotechnology*, *8*, 660.
[31] Pätzold, M., Siebenhaller, S., Kara, S., Liese, A., Syldatk, C., & Holtmann, D. (2019). Deep eutectic solvents as efficient solvents in biocatalysis. *Trends in biotechnology*, *37*(9), 943-959.
[32] Osbon, Y., & Kumar, M. (2019). Biocatalysis and strategies for enzyme improvement. *Biophysical chemistry-advance applications*.
[33] de María, P. D., de Gonzalo, G., & Alcántara, A. R. (2019). Biocatalysis as useful tool in asymmetric synthesis: An assessment of recently granted patents (2014–2019). *Catalysts*, *9*(10), 802.
[34] Hecht, K., Meyer, H. P., Wohlgemuth, R., & Buller, R. (2020). Biocatalysis in the swiss manufacturing environment. *Catalysts*, *10*(12), 1420.
[35] Fasan, R., Jennifer Kan, S. B., & Zhao, H. (2019). A continuing career in biocatalysis: Frances H. Arnold. *ACS catalysis*, *9*(11), 9775-9788.

[36] Mestrom, L., Przypis, M., Kowalczykiewicz, D., Pollender, A., Kumpf, A., Marsden, S. R., ... & Hagedoorn, P. L. (2019). Leloir glycosyltransferases in applied biocatalysis: A multidisciplinary approach. *International journal of molecular sciences*, *20*(21), 5263.
[37] Su, H., Tian, Q., Price, C. A. H., Xu, L., Qian, K., & Liu, J. (2020). Nanoporous core@ shell particles: Design, preparation, applications in bioadsorption and biocatalysis. *Nano Today*, *31*, 100834.
[38] Martin, L. L., Peschke, T., Venturoni, F., & Mostarda, S. (2020). Pharmaceutical industry perspectives on flow chemocatalysis and biocatalysis. *Current Opinion in Green and Sustainable Chemistry*, *25*, 100350.
[39] van Schie, M. M., Spöring, J. D., Bocola, M., de María, P. D., & Rother, D. (2021). Applied biocatalysis beyond just buffers–from aqueous to unconventional media. Options and guidelines. *Green Chemistry*, *23*(9), 3191-3206.
[40] Gotor-Fernández, V., & Paul, C. E. (2019). Deep eutectic solvents for redox biocatalysis. *Journal of biotechnology*, *293*, 24-35.
[41] Virgen-Ortiz, J. J., dos Santos, J. C., Ortiz, C., Berenguer-Murcia, A., Barbosa, O., Rodrigues, R. C., & Fernandez-Lafuente, R. (2019). Lecitase ultra: A phospholipase with great potential in biocatalysis. *Molecular Catalysis*, *473*, 110405.
[42] Sheldon, R. A. (2020). Biocatalysis and biomass conversion: Enabling a circular economy. *Philosophical Transactions of the Royal Society A*, *378*(2176), 20190274.
[43] Guajardo, N., & Domínguez de María, P. (2019). Continuous biocatalysis in environmentally- friendly media: a triple synergy for future sustainable processes. *ChemCatChem*, *11*(14), 3128-3137.
[44] Hall, M. (2020). Flavoenzymes for biocatalysis. *The Enzymes*, *47*, 37-62.
[45] Heath, R. S., Ruscoe, R. E., & Turner, N. J. (2022). The beauty of biocatalysis: sustainable synthesis of ingredients in cosmetics. *Natural Product Reports*, *39*(2), 335-388.
[46] Faber, K., Fessner, W. D., & Turner, N. J. (2019). Biocatalysis: ready to master increasing complexity. *Adv. Synth. Catal*, *361*, 2373-2376.
[47] Troiano, D., Orsat, V., & Dumont, M. J. (2020). Status of biocatalysis in the production of 2, 5-furandicarboxylic acid. *ACS Catalysis*, *10*(16), 9145-9169.
[48] Hollmann, F., & Fernandez- Lafuente, R. (2021). Grand challenges in biocatalysis. *Frontiers in Catalysis*, *1*, 633893.
[49] Santi, M., Sancineto, L., Nascimento, V., Braun Azeredo, J., Orozco, E. V., Andrade, L. H., ... & Santi, C. (2021). Flow biocatalysis: A challenging alternative for the synthesis of APIs and natural compounds. *International journal of molecular sciences*, *22*(3), 990.
[50] Pagar, A. D., Patil, M. D., Flood, D. T., Yoo, T. H., Dawson, P. E., & Yun, H. (2021). Recent advances in biocatalysis with chemical modification and expanded amino acid alphabet. *Chemical Reviews*, *121*(10), 6173-6245.
[51] Intasian, P., Prakinee, K., Phintha, A., Trisrivirat, D., Weeranoppanant, N., Wongnate, T., & Chaiyen, P. (2021). Enzymes, in vivo biocatalysis, and metabolic engineering for enabling a circular economy and sustainability. *Chemical Reviews*, *121*(17), 10367-10451.
[52] Bilal, M., & Iqbal, H. M. (2020). State-of-the-art strategies and applied perspectives of enzyme biocatalysis in food sector—current status and future trends. *Critical reviews in food science and nutrition*, *60*(12), 2052-2066.
[53] Federsel, H. J., Moody, T. S., & Taylor, S. J. (2021). Recent trends in enzyme immobilization—concepts for expanding the biocatalysis toolbox. *Molecules*, *26*(9), 2822.
[54] Miller, D. C., Athavale, S. V., & Arnold, F. H. (2022). Combining chemistry and protein engineering for new-to-nature biocatalysis. *Nature Synthesis*, *1*(1), 18-23.
[55] Bassanini, I., Ferrandi, E. E., Riva, S., & Monti, D. (2020). Biocatalysis with laccases: An updated overview. *Catalysts*, *11*(1), 26.
[56] Woodley, J. M. (2019). Accelerating the implementation of biocatalysis in industry. *Applied Microbiology and Biotechnology*, *103*(12), 4733-4739.

