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Halophilic Bacteria as Promising Biocatalyst Producers: A Review on Enzyme Production

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Abstract: Halophilic bacteria, a group of extremophiles adapted to high-salinity environments, have emerged as valuable sources of relevant biocatalysts. This review aims to compile and analyse current knowledge on the enzymatic potential of halophilic bacteria. Using a systematic literature review as its primary methodology to collect, examine, and integrate academic findings on halophilic bacteria as promising sources of biocatalysts. This review highlights that halophilic bacteria possess remarkable physiological and biochemical adaptations that enable them to survive osmotic stress, with recent advances in genetic engineering and synthetic biology enhancing their enzyme production and functional efficiency. These findings underscore their potential as robust and efficient biocatalysts for sustainable industrial applications. In conclusion, halophilic bacteria represent valuable resources for biotechnology, particularly in extreme conditions where conventional enzymes fail. Future research should focus on in-depth genomic and proteomic analyses, metabolic engineering for optimized enzyme yields, industrial-scale feasibility studies, environmental impact assessments, and cross-disciplinary collaborations to fully harness their capabilities in real-world applications.

Keywords: Extremophile, enzyme, halophilic bacteria, high salinity.

Pendahuluan

Halophilic bacteria are adapted to thrive in high-salinity environments and are categorized based on their optimal salt concentration for growth (Williams & Chen, 2020). These organisms have unique metabolic adaptations that allow them to survive in extreme conditions, promising sources of bioactive compounds with biotechnological and pharmaceutical potential (Corral et al., 2019). The distribution and ecology of halophilic bacteria are primarily influenced by environmental factors such as salinity and temperature, which play crucial roles in shaping their communities and habitats (Williams & Chen, 2020).

Bacteria inhabiting extreme environments have evolved adaptations to survive in harsh conditions, including high salinity, extreme temperatures, and limited nutrients (Martínez-Espinosa, 2020). Extreme habitats, such as deserts and deep-sea sediments, harbor microorganisms capable of producing novel specialized metabolites with therapeutic potential (Sayed et al., 2020). These microorganisms have developed unique adaptations and bioactive molecules to thrive in such conditions (Torres et al., 2019).

These organisms have potential in biofuel production, utilizing feedstocks considered too salty for most microbial processes (Kasirajan & Maupin-Furlow, 2021). Deep hypersaline anoxic basins (DHABs) represent some of the most extreme ecosystems on Earth, harboring polyextremophilic prokaryotes with extraordinary metabolic capabilities (Varrella et al., 2020). The study of these bacteria and their holds promise for various biotechnological applications, including the production of enzymes and novel secondary metabolites (Kasirajan & Maupin-Furlow, 2021).

Recent studies have placed growing emphasis on the detailed characterization of these enzymes to elucidate their structural and functional adaptations, as well as their activity across varying salt concentrations, pH levels, and temperature ranges. Importantly, many halophilic enzymes classified as extremozymes tolerate high salinity and maintain their function at elevated temperatures and in the presence of organic solvents. These properties make them especially attractive for biotechnological innovation, highlighting the need for ongoing research to discover and characterize new halophilic enzymes with optimized traits for industrial use.

This review aims to examine existing research on the enzyme-producing capabilities of halophilic bacteria. With the rising demand for robust and catalytically efficient enzymes capable of functioning under extreme physicochemical conditions, elucidating the enzymatic capabilities of halophilic bacteria is imperative. This review responds to the critical need for a comprehensive synthesis of current knowledge to facilitate the advancement of novel biocatalysts, thereby contributing significantly to biotechnological innovation and industrial application.

Material and Methods

This research utilizes a systematic literature review as the central methodological approach, with the objective of gathering, analyzing, and synthesizing scholarly insights related to halophilic bacteria as potential producers of biocatalysts. The review process was conducted in a methodical and unbiased manner to ensure a well-rounded and in-depth understanding of the topic. Academic sources were retrieved from established scientific databases such as ScienceDirect, SpringerLink, Wiley Online Library, PubMed, Google Scholar, and Mendeley. The literature selection prioritized studies published within the last 5 to 15 years to ensure the data's relevance and currency, while foundational works were also included where necessary to support key theoretical frameworks.

Results and Discussion

Halophilic and Halotolerant Microorganisms in Enzyme Production

Halophilic microorganisms, thriving in high-salinity environments, have garnered significant interest due to their unique adaptations and potential applications. These extremophiles produce valuable biomolecules with antimicrobial and anticancer properties (Corral et al., 2019). Their enzymes, known as extremozymes, exhibit remarkable stability under extreme conditions, making them suitable for various industrial applications (Jin et al., 2019). Halophilic archaea, in particular, are being explored for biofuel production and the generation of value-added products like antibiotics, carotenoids, and bioplastic precursors (Kasirajan & Maupin-Furlow, 2021). The increasing demand for novel bioactive compounds has led to the development of advanced sequencing and genome mining tools to identify and characterize halophilic prokaryotes and their valuable biological products (Lach et al., 2021). These organisms' unique metabolism and adaptability to harsh conditions make them promising candidates for biotechnological, pharmaceutical, and industrial applications in addressing global challenges such as antibiotic resistance and environmental pollution.

Halophilic and halotolerant microorganisms have gained significant attention for their potential in various industrial applications, particularly in biofuel production. These microbes can thrive in high-salt environments and possess unique adaptations that make them valuable for bioconversion processes (Amoozegar et al., 2019). Halophilic archaea and their enzymes are especially promising for generating biofuels and value-added products from diverse feedstocks, including those considered too salty for conventional microbial processes(Kasirajan & Maupin-Furlow, 2021). Additionally, electroactive halophilic bacteria show potential for renewable energy generation and self-powered biosensing in high-saline environments (Gaffney et al., 2021). Beyond industrial applications, halotolerant bacteria play a crucial role in enhancing crop plant tolerance to salinity stress, offering promising solutions for sustainable agriculture in salt-affected areas (Ramasamy & Mahawar, 2023). The unique capabilities of these microorganisms make them highly suitable for addressing various environmental and industrial challenges in high-salt conditions.

Extremophiles are microorganisms that thrive in harsh environments, producing enzymes with superior stability compared to those from mesophilic sources (Kohli et al., 2020). These extremozymes, including cellulases, xylanases, and laccases, exhibit enhanced stability under extreme conditions, making them valuable for industrial applications (Espina et al., 2021). Prokaryotic endoxylanases, for instance, demonstrate broad pH and temperature tolerance, cellulase-free activity, and longer stability, making them preferable to fungal sources (Verma, 2021). Extremozymes have diverse applications, such as bio-bleaching of paper pulp, bioconversion of lignocellulosic biomass, and improving bakery products (Verma, 2021). However, studying extremophiles is challenging due to cultivation difficulties. Culture-independent methods like sequence-based metagenomics and single amplified genomes have emerged as valuable tools for discovering novel extremozymes from uncultivable organisms, expanding our understanding of life in extreme conditions and potential biotechnological applications (Sysoev et al., 2021).

Halophilic archaea and fungi from hypersaline environments are emerging as valuable sources of bioactive compounds and enzymes with industrial and therapeutic potential. These extremophiles produce unique metabolites and enzymes that remain functional under harsh conditions, making them attractive for bioconversion processes and biofuel production (Kasirajan & Maupin-Furlow, 2021). Haloarchaea synthesize various bioactive molecules, including carotenoids, enzymes, and bioplastics, with applications in biotechnology and medicine (Moopantakath et al., 2023). Similarly, halophilic fungi yield diverse compounds with cytotoxic, antimicrobial, and antioxidant properties (Agrawal et al., 2024). Despite their potential, many extremophiles remain uncultivable, limiting their exploration. Culture-independent methods like sequence-based metagenomics and single amplified genomes are now enabling the discovery of novel extremozymes from previously inaccessible microorganisms(Sysoev et al., 2021). These advances are expanding our understanding of extremophiles and their biotechnological applications in various industries.

Cellulases play a crucial role in bioethanol production from lignocellulosic biomass by hydrolyzing cellulose into fermentable sugars (Ilić et al., 2023). Recent research focuses on improving microbial cellulase production and developing more effective enzyme mixtures for industrial applications (Ilić et al., 2023). The yeast Clavispora NRRL Y-50464 has shown promise as a dual-functional biocatalyst, producing β-glucosidases and tolerating inhibitory compounds associated with lignocellulose conversion (Liu & Dien, 2022). Saccharomyces cerevisiae remains the preferred microorganism for ethanol production and has been extensively genetically modified to improve its performance in second-generation bioprocesses (Cunha et al., 2020). Ongoing research aims to optimize S. cerevisiae strains for efficient xylose consumption and consolidated bioprocessing, which could lead to more economically viable lignocellulosic bioethanol production (Cunha et al., 2020). These advancements in enzyme and microbial technologies are essential for the development of a sustainable bioeconomy based on renewable biomass resources.

Extremophilic microorganisms, particularly thermophiles, are valuable sources of industrially important enzymes like cellulases and xylanases (Mohanta et al., 2023). These enzymes exhibit enhanced stability under harsh conditions, making them suitable for various biotechnological applications (Kohli et al., 2020). Thermostable cellulases and xylanases play a crucial role in lignocellulose bioconversion, which is essential for biofuel and bioproduct manufacturing (Ajeje et al., 2021) Recent advancements in genetic engineering and synthetic biology have enabled the production of these enzymes in mesophilic hosts and improved their catalytic activity and thermostability(Ajeje et al., 2021) (Zhu et al., 2020). Extremophiles and their enzymes have significant potential in biorefinery processes, including pretreatment, saccharification, fermentation, and lignin valorization (Zhu et al., 2020). However, challenges remain in producing commercially valuable thermostable enzymes in sufficient quantities, necessitating further research and development to accelerate their industrial application (Ajeje et al., 2021) (Zhu et al., 2020). Extremophilic microorganisms and their enzymes have gained significant attention for their potential in biorefinery and biofuel production due to their ability to withstand harsh industrial conditions (Zhu et al., 2020).

These organisms, including thermophiles, psychrophiles, alkaliphiles, acidophiles, and halophiles, possess unique structural, physiological, and genomic features that enable them to thrive in extreme environments (Kohli et al., 2020). Their enzymes, such as amylases, lipases, xylanases, cellulases, and proteases, exhibit enhanced stability and activity under challenging conditions, making them valuable for various industrial applications (Kohli et al., 2020) (Verma, 2021). Prokaryotic endoxylanases, in particular, have shown promise in bio-bleaching, lignocellulosic biomass conversion, bioethanol production, and food processing (Verma, 2021). Halophilic microorganisms have demonstrated potential in producing bioethanol, biobutanol, biodiesel, and biogas from various organic substrates (Amoozegar et al., 2019). The development of extremophiles and their enzymes for biorefinery applications is ongoing, with efforts to optimize metabolic pathways and improve production efficiency (Zhu et al., 2020).

Halophilic and extremophilic microorganisms, particularly bacteria and archaea, have significant potential for industrial applications, especially in biofuel production (Amoozegar et al., 2019) (Kasirajan & Maupin-Furlow, 2021). These organisms and their enzymes, including α-amylase, can operate under harsh conditions such as high salt concentrations, extreme pH, and high temperatures, making them valuable for bioconversion processes (Zhu et al., 2020) (Elyasi Far et al., 2020). Their unique traits enable the production of bioethanol, biodiesel, and other value-added products from various feedstocks, including lignocellulosic biomass and industrial wastes (Kasirajan & Maupin-Furlow, 2021) (Zhu et al., 2020). Extremophilic enzymes play crucial roles in pretreatment, saccharification, fermentation, and lignin valorization processes (Zhu et al., 2020). Ongoing research focuses on improving enzyme production and stability through genetic engineering and optimization methods like RSM (Elyasi Far et al., 2020). The development of these microbial resources and their enzymes is essential for advancing biorefinery technologies and reducing dependence on fossil fuels (Amoozegar et al., 2019).

Recent research on halophilic bacteria focuses on enhancing their industrial applicability through advanced genetic engineering tools and synthetic biology approaches. The CRISPR/Cas9 system has emerged as a breakthrough technology for efficient genetic engineering in industrial microorganisms, enabling the construction of complex gene circuits (Zhang et al., 2020). Genome mining and sequencing techniques are being employed to identify valuable bioproducts and functions in halophilic genomes, addressing the demand for new effective compounds in various industries (Lach et al., 2021). Researchers are also exploring the use of halophilic bacteria in electrochemical systems for renewable energy generation and biosensing in high-saline environments (Gaffney et al., 2021). However, challenges remain in deconvoluting halophilic metagenomes due to their high G+C content and intraspecific diversity. To overcome these obstacles, new experimental and analytical strategies are being developed, including the application of RNA sequencing and long-read technologies (Uritskiy & DiRuggiero, 2019).

Recent advances in enzyme engineering have significantly improved the applicability of enzymes in various fields. Rational protein design and directed evolution techniques have been employed to enhance enzyme properties such as stereoselectivity, stability, and substrate specificity (Reetz, 2022). For lipases, modifying amino acid sequences in the binding pocket or lid region has led to improved substrate specificity and enantioselectivity (Albayati et al., 2020). In the case of DNA polymerases, particularly archaeal family B polymerases, engineering efforts have focused on enhancing their performance in PCR, synthesis of xeno-nucleic acids, and reverse transcription (Kuznetsova & Kuznetsov, 2023). These modifications have expanded the toolbox for organic chemists and biotechnologists, enabling more reliable and efficient enzymatic processes. The optimization of reaction conditions, coupled with enzyme engineering, has also contributed to improving the sensitivity, specificity, and fidelity of nucleic acid amplification methods (Yasukawa et al., 2020).

Defence Mechanisms of Halophilic Bacteria

Halophilic microorganisms have developed sophisticated mechanisms to survive in high-salinity environments. These adaptations include the accumulation of compatible solutes, which help maintain turgor pressure and stabilize macromolecules under osmotic stress (Bremer & Krämer, 2019). Haloarchaea, in particular, synthesize stress proteins to protect against protein denaturation caused by various environmental stressors, including salinity changes (Matarredona et al., 2020). The ability to withstand osmotic stress is crucial for the persistence of pathogens like Acinetobacter baumannii in hospital settings (Zeidler & Müller, 2019). Interestingly, halophilic microorganisms produce bioactive metabolites with potential pharmaceutical applications, such as antimicrobial and anticancer compounds (Corral et al., 2019). Recent research has revealed novel insights into the regulatory pathways and enzymes involved in osmotic stress resistance, including the bifunctional enzyme MtlD in A. baumannii, which synthesises the unusual compatible solute mannitol (Zeidler & Müller, 2019).

Ectoine, a key osmoprotectant, plays multifunctional roles in halophilic microorganisms, acting as a protein stabiliser, DNA protectant, and antioxidant (Hermann et al., 2020). Its biosynthesis and degradation pathways have been extensively studied, revealing the importance of N-acetyldiaminobutyric acid isomers in synthesis and catabolism regulation (Hermann et al., 2020). Halophiles produce various bioactive metabolites with potential pharmaceutical applications, including antimicrobial and anticancer compounds (Corral et al., 2019). To cope with environmental stressors, haloarchaea have developed adaptive mechanisms involving stress proteins, such as heat shock proteins and universal stress proteins (Matarredona et al., 2020). These adaptations allow halophytes to thrive in high-salinity environments and have potential applications in improving crop salt tolerance through gene transfer (Rahman et al., 2021). The study of halophilic adaptations continues to be crucial for biotechnological advancements and sustainable agriculture in saline soils (Rahman et al., 2021).

Ectoine, a bacterial-derived compatible solute, has gained significant attention in biotechnology and cosmetics due to its protective and stabilizing properties. Its applications extend from pharmaceutical formulations to skincare products, leveraging its moisturizing and anti-inflammatory effects (Bilstein et al., 2021). In ophthalmology, ectoine-containing eye drops have shown efficacy in treating ocular surface irritations and inflammations (Bilstein et al., 2021). The industrial production of ectoine has been developed to meet increasing market demands, with ongoing research focusing on cost-effective and sustainable large-scale production methods (Ng et al., 2023). Ectoine's versatility as both a stress protectant and nutrient in microorganisms has led to extensive studies on its biosynthesis and degradation pathways (Hermann et al., 2020). In the cosmetics industry, fermentation-based production of ectoine aligns with the shift towards more sustainable and bio-based ingredients, addressing regulatory and consumer demands for environmentally friendly products (Pérez-Rivero & López-Gómez, 2023).

Halophilic microorganisms have evolved diverse strategies to thrive in hypersaline environments, including the production of osmoprotectants like ectoine (Hermann et al., 2020). These extremophiles are valuable sources of bioactive compounds with potential applications in biotechnology, pharmaceuticals, and industry (Corral et al., 2019). Recent advances in sequencing and genome mining tools have facilitated the discovery of novel biomolecules from halophiles, addressing the urgent need for new antimicrobial and anticancer agents (Lach et al., 2021) Halophilic microbes, such as Bacillus, Actinobacteria, Halorubrum, and Aspergillus, produce a wide range of antimicrobial compounds that show promise against drug-resistant pathogens (Santhaseelan et al., 2022). The unique metabolic adaptations of halophiles to extreme conditions, including high salinity, UV radiation, and toxic compounds, make them attractive candidates for drug discovery and development of novel therapeutic agents (Santhaseelan et al., 2022).

Recent advances in genomics and transcriptomics have enabled researchers to identify and characterize genes and pathways related to stress tolerance in extremophiles, including halophilic bacteria (Lach et al., 2021). These findings are crucial for synthetic biology approaches aimed at engineering robust microbial strains capable of functioning under industrially relevant stresses (Zhu et al., 2020). By transferring genes responsible for stress tolerance into non-halophilic industrial strains, scientists can create biofactories that combine the metabolic efficiency of model organisms with the stress tolerance of extremophiles (Fatma et al., 2020). This approach has applications in biorefinery processes, where extremophiles and their enzymes can be used for pretreatment, saccharification, fermentation, and lignin valorization (Zhu et al., 2020). Similar strategies are being applied in agriculture to develop abiotic stress-resilient crops using genomics and transcriptomics tools, contributing to sustainable agriculture and food security (Kamali & Singh, 2023).

Halophilic bacteria possess remarkable defense mechanisms that enable their survival in extreme environments, offering valuable insights for industrial biotechnology. These microorganisms synthesize compatible solutes like ectoine, which serve as cytoprotectants during osmotic stress and temperature extremes (Hermann et al., 2020). Ectoine has numerous applications in cosmetics, food, and biotechnology, driving the development of cost-effective production methods (Ng et al., 2023). Extremophilic bacteria, including halophiles, play crucial roles in biorefinery processes, providing novel metabolic pathways and robust enzymes for harsh industrial conditions (Zhu et al., 2020). Additionally, electroactive halophilic bacteria show promise in microbial fuel cells for renewable energy generation and self-powered biosensing in high-saline environments (Gaffney et al., 2021). These adaptations of halophilic bacteria offer potential for enhancing microbial productivity and stress resistance in various sectors, including biofuels, pharmaceuticals, and food processing.

Conclusion

Halophilic and halotolerant bacteria represent a valuable and underutilized resource in industrial biotechnology. Their ability to produce active and stable enzymes under extreme conditions, such as high salinity, temperature, and variable pH, offers significant advantages over non-extremophilic sources. Salt-tolerant enzymes have demonstrated potential in diverse industrial applications, including biofuel production, biomass degradation, and bioremediation. Moreover, these microorganisms' natural resilience and adaptability make them excellent candidates for genetic and metabolic engineering to enhance enzyme yield and performance further. Continued exploration and characterization of halophilic bacterial strains and modern biotechnological tools will be crucial for unlocking their full potential as biocatalyst producers. This research underscores the importance of halophilic bacteria as promising contributors to developing more sustainable and efficient bioprocesses.

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