ISSN 1983 1501, DOI: 10.7867/1983-1501.2023V25N1P48-66

REA - Revista de estudos ambientais (Online)
v. 25, n. 1, p.48-66, jan./jun. 2023

MICROBIAL LIPASES: PROPITIOUS BIOCATALYSTS FOR VARIOUS BIOTECHNOLOGICAL APPLICATIONS

Lipases microbianas: biocatalisadores propícios para diversas aplicações biotecnológicas

Jéssyca Ketterine Carvalho[1,2]; Joel Gustavo Teleken[2]; Paulo Menegotto dos Santos[1], Maria Luiza Fernandes Rodrigues[1]; Cleide Viviane Buzanello Martins[1]

Abstract: Microbial lipases are versatile biocatalysts, catalyzing reactions in both aqueous and non-aqueous media, offering advantages like specificity, enantioselectivity, and stability at various pH levels and temperatures. These enzymes are crucial across industries such as food, cosmetics, pharmaceuticals, biofuels, and environmental management. Solid-state fermentation (SSF) stands out as a promising method for producing lipases, utilizing agro-industrial residues as cost-effective substrates. SSF not only reduces production costs but also produces more concentrated biocatalysts, simplifying their recovery. This work reviews the potential of microbial lipases, focusing on their production via SSF. This review used PubMed, Scopus, and Google Scholar (2005-2024), focusing on microbial lipases, fermentation techniques, and relevant studies on lipase characteristics and applications. Immobilizing lipases in fermented solids reduces costs and enhances their industrial applicability, aligning with green chemistry principles by minimizing waste and environmental impacts. The diversity of microorganisms and substrates used in SSF makes the process adaptable and viable for various industrial applications. Lipases produced through SSF using regionally available agro-industrial residues provide a sustainable and economically feasible solution for industrial processes. This review underscores the essential role of microbial lipases in optimizing industrial practices, promoting sustainability, and reducing environmental impacts, making them indispensable in modern industrial applications.

Resumo: Lipases microbianas são biocatalisadores versáteis, catalisando reações em meios aquosos e não aquosos, oferecendo vantagens como especificidade, enantiosseletividade e estabilidade em vários níveis de pH e temperaturas. Essas enzimas são cruciais em indústrias como alimentos, cosméticos, produtos farmacêuticos, biocombustíveis e gestão ambiental. A fermentação em estado sólido (SSF) se destaca como um método promissor para a produção de lipases, utilizando resíduos agroindustriais como substratos econômicos. A SSF não apenas reduz os custos de produção, mas também produz biocatalisadores mais concentrados, simplificando sua recuperação. Este trabalho analisa o potencial das lipases microbianas, com foco em sua produção via SSF. A imobilização de lipases em sólidos fermentados reduz custos e aumenta sua aplicabilidade industrial, alinhando-se aos princípios da química verde ao minimizar o desperdício e os impactos ambientais. A diversidade de microrganismos e substratos usados na SSF torna o processo adaptável e viável para várias aplicações industriais. Lipases produzidas por meio de SSF usando resíduos agroindustriais disponíveis regionalmente fornecem uma solução sustentável e economicamente viável para processos industriais. Esta revisão ressalta o papel essencial das lipases microbianas na otimização de práticas industriais, promovendo a sustentabilidade e reduzindo impactos ambientais, tornando-as indispensáveis em aplicações industriais modernas.

Keywords:

Enzyme;
Lipase biocatalyst;
Catalytic activity;
Biotechnology.

Palavras-chave:

Enzima;
Biocatalisador lipase;
Atividade catalítica;
Biotecnologia.

---

[1]State University Western Paraná, Engineering and Exact Sciences Center, Toledo/PR, Brazil.
[2]Federal University of Paraná, Department of Engineering and Exact, Palotina/PR, Brazil.
E-mail – jessycakcarvalho@gmail.com[1]

1 INTRODUCTION

Enzymes are biological catalysts that accelerate the speed of chemical reactions and metabolic processes, have high specificity, and are highlighted in the area of bioprocess technology (Taheri-Kafrani et al., 2020). Most enzymes are proteins, but some are considered ribonucleic acids and classified according to their catalysis reactions as oxidoreductases (oxide reduction), transferases (transfer of groups of molecules), hydrolases (hydrolysis), lyases (bond breaking), isomerases (intramolecular change), ligases (formation of a covalent bond between two molecules with high energy consumption) and Translocases (assists in moving another molecule) (Cai & Chou, 2005; Tao, Dong, Teng & Zhao, 2020).

The use of biological catalysts (enzymes) has become a viable option and the interest in this area is growing more and more due to their physicochemical characteristics (Thapa et al., 2019), with higher biodegradability, application in milder conditions, high recoverability in the process (Czaja, 2015; Grajales-Hernándes et al., 2020; Shakerian, Zhao & Li, 2020), in addition to their ability of chemoselectivity, enantioselectivity, and regioselectivity (Tong, Busk & Lange, 2015; Kretschmann, Bester, Bollmann, Dalhoff & Cedergreen, 2019; Girelli, Astolfi & Scuto, 2020).

There is a growing search for viable alternatives for obtaining enzymes, especially those derived from microorganisms, as they tend to be environmentally friendly and economically relevant when compared to enzymes of animal and plant origin (Vyas & Chhabra, 2017; Carvalho et al., 2021). Moreover, microorganisms are the main sources of enzymes due to easy procurement, wide availability, simple nutritional requirements, rapid growth rate, and diversity in catalytic activities (Thapa et al., 2019).

Among the enzyme groups, hydrolases are widely used in the industrial field (Amadi et al., 2020), and lipolytic enzymes (belonging to hydrolases) are the third most widely used group of catalysts, due to their high efficiency in aqueous and organic media, reduced reaction times, and low production costs, they are essential as biocatalysts in biotechnology. (Kumar, Das, Giri & Verma, 2020; Carvalho et al., 2024a). The high versatility of lipases allows applications in various sectors such as the food industry (Zhang et al. 2018), pharmaceutical (Naghdi et al., 2018), textile, pulp and paper, dairy, detergent (and other cleaning products) manufacturing, new polymeric materials, wastewater treatment and biofuels (Bharathi & Rajalakshmi, 2019; Kumar, Das, Giri & Verma, 2020).

Lipases, belonging to the α/β-hydrolase family, are enzymes that do not require cofactors for their activity and remain stable in organic solvents. Their high efficiency in aqueous and organic media, reduced reaction times, and low production costs make them attractive as biocatalysts in biotechnology (Dickel et al., 2022). Additionally, they are considered a clean technology due to their high specificity and wide availability (Carvalho et al., 2024b).

Given this, studies are emerging with new supports to immobilize the enzymes, such as agroindustrial waste, which can be more viable alternatives of support for enzyme immobilization, because besides being a more economical way to make the process viable, it will also help in the problems of disposal and disposal of waste, following the principles of green chemistry (Doble et al., 2020).

Thus, this paper aims to discuss and review studies on microbial lipases, with direct application of the fermented solid, focusing on the main microorganisms, substrates and supports used in SSF and the applicability of lipases in various industrial sectors.

2 METHOLOGY

This literature review was conducted based on searches in the PubMed, Scopus, and Google Scholar databases, covering the period from 2005 to 2024. The review included original articles, review articles, and digital books that discuss the production and application of microbial lipases, with a focus on fermentation.

The inclusion criteria used for selecting studies were their relevance to the subject, prioritizing publications that significantly contribute to the understanding of lipase characteristics and solid-state (SSF) and submerged (SF) fermentation techniques.

The search strategies involved using keywords such as "fermentation," "enzymes," "lipase," "microorganisms," and "biocatalysts." These keywords were combined to refine the search results and identify the most relevant studies.

The review was organized into five main sections: (1) structure and characteristics of lipases, (2) bacterial-origin lipases, (3) fungal-origin lipases, (4) yeast-origin lipases, and (5) analysis of solid-state (SSF) and submerged (SF) fermentation techniques. This organization allowed for a systematic and comprehensive approach, covering different aspects and sources of microbial lipases, as well as a detailed comparison between fermentation techniques.

3 RESULTS

3.1 Lipase structures and characteristics

Lipases (EC 3.1.1.3) also known as triacylglycerol ester hydrolases are abundant in nature and belong to the group of enzymes of the serine hydrolase category (Bharathi, Rajalakshmi & Komathi, 2018). Their molecular weight is in the range of 19 kDa to 60 kDa besides being described as monomeric proteins (formed by only one polypeptide chain) (Chandra, Singh & Arora, 2020), and what differentiates lipases from other types of esterases is the ability to hydrolyze water-insoluble esters (Kartal, 2016).

The essential structural elements of lipases are a binding pocket, cap, oxy-anion hole, and disulfide bridge. The binding pocket is hydrophobic and is related to enzyme activity (Faryad, Ataa, Joyia & Parvaiz, 2021). The cap is important for determining molecular activity and selectivity in addition to interfacial activation (Khan et al., 2017), the oxy-anion hole is of utmost importance as it is this region that can influence the catalytic efficiency of lipases (Gao et al., 2011) and the disulfide bridge contributes to conformational stability, decreasing entropy and influencing the thermal stability of the enzyme (Tambunan, Randy & Parikesit, 2014).

Lipases have the characteristic of increasing catalytic activity at the water-oil interface, a process known as interfacial activation, involving a structural rearrangement of conformation from inactive to active (Khan et al., 2017). With this, catalysis is initiated by anchoring the lipase at the oil-water interface through the exposed hydrophobic area (Priyanka, Tan, Kinsella, Henehan & Ryan, 2018).

Thus, lipases can catalyze hydrolysis and synthesis of triglycerides, diacylglycerol, monoacylglycerol, and glycerol, and also exhibit hydrolysis, interesterification, esterification, aminolysis, acidolysis, and alcoholysis activities (Javed et al., 2018). In addition to the aforementioned potential, lipases synthesize glycerol esters as well as long-chain fatty acids in a non-aqueous medium, contributing to a wide range of industrial applications (Chandra, Singh & Arora, 2020).

Also at the oil-water interface, lipase has the ability to hydrolyze triglycerides, thus converting them into glycerol and fatty acids, and has properties that reverse this reaction in aqueous and non-aqueous media (Lee et al., 2015; Ramos-Sanches, Cujilema-Quitio, Julian-Ricardo, Cordova & Fickers, 2015). The efficiency of lipases depends on the physical properties and factors such as the position of the fatty acid in the glycerol structure, chain length, and degree of unsaturation (Tong, Busk & Lange, 2015; Bonomi, Iametti & Marengo, 2019).

Given the advantageous characteristics that lipases have as catalysts, these enzymes are in third place in industrial applications, behind proteases and amylases (carbohydrases), this is due to their great versatility (Javed et al., 2018; Arora, Mishra & Mishra ,2020). The efficiency of the application of lipases will also depend on the origin, being microbial (bacteria, fungi, and yeast) the most used (Vyas & Chhabra, 2017).

3.2 Lipases of bacterial origin

In the industrial area, lipases can come from bacteria, which in most cases are considered safe and do not produce toxins (Niyonzima & More, 2020). Bacterial lipases are less diverse compared to fungal lipases and are more limited in industry, however, they are still in high demand due to their yield and ability to work in alkaline pH (Bharathi, Rajalakshmi & Komathi 2018).

In most bacteria, the lipases produced by them are affected by polysaccharides found in the medium, and usually, these lipases are glycoproteins, but in some cases of extracellular lipases, their nature is considered lipoprotein (Chandra, Singh & Arora, 2020). Extracellular lipases coming from bacteria will depend on some nutritional and physicochemical factors such as carbon and nitrogen sources, oxygen, lipids, incubation time, and pH, among others (Arora, Mishra & Mishra, 2020).

Among the genera with the ability to produce lipases, the best known are *Bacillus*, *Burkholderia, Pseudomonas* and *Staphylococcus* (Bouaziz, Horchani, Salem, Gargouri & Sayari, 2011; Sagar, Bashir, Phukan & Konwar, 2013; Arora, Mishra & Mishra, 2020). In addition to these genera, others such as *Achromobacter* spp., *Alcaligenes* sp., *Arthrobacter* spp.*, and Chromobacterium* spp. are also sources of lipase production (Chandra, Singh & Arora, 2020). In Table 1, we can see some species of lipase-producing bacteria and their respective applications in industry.

Table 1 - Bacterial species that produce lipases and their applications in biotechnology

Bacterial species	Applications	References
Achromobacter sp.	Oily wastewater treatment.	(Deng et al., 2020).
Bacillus aerius	Production of biodiesel.	(Bhan & Singh, 2020).
Bacillus cereus	Wastewater treatment.	(Durval et al., 2020).
Bacillus sp.	Food industry.	(Balaji, Chittoor & Jayaraman, 2020).
Bacillus subtilis and Bacillus thermocatenulatus	Medical Industry.	(Su, Fang & Zhang, 2020).
Burkholderia cepacia	Production of biodiesel.	(Ostojčić et al., 2020).
Geobacillus stearothermophilus	Detergent formulation.	(Abol-Fotouh, AlHagar & Hassan, 2021).
Lactobacillus casei	Cheese industry (flavorings).	(Souza, Ribeiro & Coelho, 2019).
Pseudomonas cepacia and Pseudomonas sp.	Production of biodiesel.	(Kumar, Das, Giri & Verma, 2020; Khosla et al., 2017).
Serratia marcescens	Manufacture of detergent and biodiesel.	(García-Silvera et al., 2018).
Staphylococcus aureus	Detergent industry.	(Bacha, Al-Assaf, Moubayed & Abid. 2018).

Within the family *Bacillaceae*, bacteria belonging to the genera *Bacillus* and *Geobacillus* are the main sources of lipase production. Bacteria of the genus *Bacillus* have great potential for biotechnological applications due to their properties, such as cells that adapt to survive in extreme climatic conditions (Guncheva & Zhiryakova, 2011).

Lipase from *Bacillus* species occurs by SF (Chakraborty & Raj, 2008; Berekaa, Zaghloul, Abdel-Fattah, Saeed & Sifour, 2009). Its cells are grown in a nutrient medium rich in carbon, nitrogen, phosphorus, and mineral salts (Ebrahimpour, Rahman, Ch'ng, Basri & Salleh, 2008), as well as lipids (olive, mustard, soybean, rice bran, cottonseed, sesame and corn oil) and free fatty acids (oleic acid) (Guncheva & Zhiryakova, 2011).

3.3 Lipase from yeast and filamentous fungi

Lipases from yeast are widely used in the industrial arena as they are considered safe and non-toxic (Melani, Tambourgi & Silveira, 2018). Moreover, they have unique applications in the chemical and pharmaceutical sectors, biodiesel production, and the food industry (Singh & Mukhopadhyay, 2012).

Most yeasts possess the ability to produce lipases (Alami et al., 2017), but the main producing genera are *Candida, Rhodotorula, Yerrowia, and Trichosporon*. In addition to the above, other yeast genera are considered good lipase producers such as *Saccharomyces, Torulospora, Kluyveromyces, Pseudozyma, Pischia, Lachancea, and Zygosaccharomyces* (Moftah et al., 2012; Nagarajan, 2012; Divya & Padma, 2015; Lan, Qu, Yang & Wang, 2016; Su, Fang & Zhang, 2020).

Yeasts of the genus *Candida* are highlighted with great industrial potential for the production of extracellular lipase and have as an advantage the ability to act in long-chain ester, hydrolyzing and synthesizing with these, various types of oils (Alami et al., 2017). Within this genus, there are species considered excellent lipase producers and with greater potential within the category of yeasts, containing several reports in the literature on their properties, structures, and catalytic actions (Bharathi & Rajalakshmi, 2019).

The *Candida* genera also possess the ability to hydrolyze nonspecific triacylglycerols that are found abundantly in nature. With this, several species of this genus are widely studied for their ability to produce extracellular lipase such as *C. albicans, C. antarctica, C. deformans* CBS 2071*, C. curvata, C. rugosa, C. albidus, C. laurentii, C. zeylanoides, C. famata, C. lipolytica* (Alami et al., 2017).

Several species of yeast and filamentous fungi are good lipase producers with simple extraction, purification, and processing steps (Roy, Kumar, Ramteke & Sit, 2018). Filamentous fungi have as a characteristic, the ability to produce extracellular enzymes, thus making them an attractive source for enzymes of industrial interest such as lipases (Gutarra et al., 2008).

Genera of filamentous fungi such as *Penicillium, Rhizopus, Aspergillus, Fusarium, Mucor* and *Geotrichum* are examples of lipase producers with potential application in various industrial areas (Mahmoud, Koutb, Morsy & Bagy, 2015; Çakmak & Aydoğdu, 2021). In Table 2 we can observe some yeast and filamentous fungi species and their applicability in the industrial field.

Table 2 - Yeast and filamentous fungi species that produce lipases and their applicability in biotechnology

Yeast and filamentous fungi species	**Applications**	**References**
Candida rugosa	Synthesis of flavor and aroma esters, biodiesel production, and other chemical producer syntheses.	(Bayramoglu, Celikbicak, Kilic & Arika, 2022; Subroto, Indiarto, Pangawikan, Huda & Yarlina, 2020).
Candida antarctica	Production of biodiesel, detergent, food, chemical industry, among others.	(Shahedi, Yousefi, Habib, Mohammadi & habi, 2019; Monteiro et al., 2021).
Yerrowia lipolytica	Flavoring esters, wax esters biolubricants, food industry, biosensors, biodiesel.	(Souza, Ribeiro & Coelho, 2019; Madzak, 2018).
Rhodotorula sp.	Formulation of detergents.	(Maharana & Singh, 2017).
Trichosporon sp.	Synthesis of structured triacylglycerols, surfactants, food additives, biofuels, lubricants and detergents.	(Cao et al., 2021).
Saccharomyces cerevisiae	Bioremediation.	(Massoud, Hadiani, Hamzehlou & Khosravi-Darani, 2018).
Aspergillus niger	Food industry and biodiesel production.	(Feng et al., 2020).

Yeast and filamentous fungi species	**Applications**	**References**
Penicillium sp.	Bioremediation and Biodegradation.	(Kumar, Das, Giri & Verma, 2020; Sarmah et al., 2017; Ostojčić et al., 2020).
Penicillium sp.	Bioremediation and Biodegradation.	(Barnes, Khodse, Lotlikar, Meena & Damare, 2017).
Penicillium roqueforti and *Penicillium camemberti*	Cheese manufacturing.	(Kumura et al., 2019).
Geotrichum candidum	Chemical industry.	(Brabcová et al., 2013).
Rhizopus oryzae	Production of structured lipids, biodiesel and flavor esters.	(López-Fernandez, Benaiges & Valero, 2020).
Fusarium spp.	Chemical industry.	(Rana et al., 2019).
Fusarium incarnatum	Bioremediation.	(Joshi, Sharma & Kuila, 2019).
Mucor miehei	Production of biodiesel.	(Carteret, Jacoby & Blin, 2018).

Filamentous fungi vary in their lipolytic production depending on the strain, presence of inducer, carbon and nitrogen sources, pH, NaCl concentration, and temperature, among other medium conditions that make it indispensable in obtaining the best yield of extracellular enzymes (Wadia & Jain, 2017). Fungal lipase production can occur by SF or SSF, but filamentous fungi are more adapted to growth in solid-state fermentation than other microorganisms such as bacteria and yeast (Edwinoliver et al., 2010).

3.4 Analysis of fermentation techniques for lipase production

The fermentative processes for lipase production (SF and SSF) are widely used in obtaining products, mainly from the industrial sector, this being an approach that uses microorganisms for biological transformations of complex substrates into simpler molecules (Bharathi & Rajalakshmi, 2019). Both are conventional techniques used for lipase production and each of them has its advantages and peculiarities (Faryad, Ataa, Joyia & Parvaiz, 2021).

3.5 Submerged Fermentation (SF)

In the process of SF, microorganisms are found in normally liquid media, presenting greater homogeneity in the culture medium, and parameters such as temperature and pH are easily controlled, and the concentration of dissolved nutrients is well defined. The extracellular production of SF is based on the optimization of carbon source, nitrogen, oils, and surfactants, in addition to physicochemical parameters such as pH and temperature, and incubation time (Geoffry & Achur, 2018).

Lipases from SF are generally more thermostable than those obtained by the SSF process, making them suitable for industrial applications involving high temperatures, in addition, lipase production by SF generates fewer undesirable metabolites such as phenolic compounds, phenolic acids, and flavonoids than SSF (Colla et al., 2015). Thus, SF is the most widely used method for obtaining enzymes of industrial interest because it has advantages such as easy large-scale obtainability (Alabdalall, ALanazi, Aldakeel, AbdulAzeez & Borgio, 2020). In addition, lipase from SF can be subjected to drying techniques to obtain a dry extract of the enzyme, making it more durable and increasing its shelf life (Utami, Hariyani, Alamsyah & Hermansyah, 2017).

3.6 Solid-State Fermentation (SSF)

Solid-state fermentation involves the use of a solid matrix and the process is carried out in the absence or near absence of free water, so for microorganisms to thrive, the substrate or support must contain moisture and provide the nutrients necessary to keep their metabolism active and provide for their growth (Vandenberghe et al., 2021).

Agricultural and forestry residue substrates such as cereal grains, legume seeds, bran such as oatmeal and soybean meal, cakes (press cake or oil cake are the solid residues obtained after processing oilseeds), sugarcane and cassava bagasse, fruit and coffee pulp and peel, straws, sawdust, wood chips, materials of plant and animal origin, is the most commonly used in the process of SSF and most of them have low cost, are easily obtained and provide all necessary nutrients for the growth of microorganisms (Farinas, 2015; Sadh, Duhan & Duhan. 2018; Paluzar, Tuncay & Aydogdu, 2021).

This type of fermentation can be considered an economical way, using relatively simple substrates in the production of extracellular enzymes, mainly coming from filamentous fungi by providing a similarity to their natural habitat, in which microorganisms will grow and release in their metabolism, products with high added value (Steudler, Werner & Walther, 2019).

The main advantages of using SSF are lower susceptibility to contamination, lower sterilization requirements, higher enzyme productivity, lower susceptibility to substrate inhibition, use of agro-industrial wastes (such as those mentioned above), lower effluent production, higher substrate quality and activity without the need for the addition of organic solvents, making the process more environmentally friendly and economical (Soccol et al., 2017).

In contrast, we can cite negative points regarding the use of SSF, such as a limited number of species that can thrive in environments with reduced humidity (Faryad, Ataa, Joyia & Parvaiz, 2021).

When considering the wide applicability of lipase and the few areas covered by SSF lipases, we can observe the need for further exploration (Aguieiras, Cavalcanti-Oliveira, Cammarota & Freire, 2018). In Table 3 we can observe some works using fermented solids and their applications

Table 3 - Fermented solid lipases from microorganisms and their applications in biotechnology

Species of microorganisms	**Fermented solid**	**Applications**	**References**
Aspergillus ibericus	Palm kernel and sesame oil pie mixes	Flavor Esters	(Oliveira et al., 2017).
Aspergillus ibericus	Palm kernel oil pie and other types of oil pies	Flavor Ester Production	(Oliveira et al., 2017).
Aspergillus niger	Wheat bran / Corn cob	Bioremediation	(Kreling, Simon, Fagundes, Thomé & Colla, 2020).
Aspergillus niger	Canola Pie	Cooking oil waste treatment	(Preczesk et al., 2018).
Aspergillus niger	Copra residue (dried coconut pulp)	Wastewater treatment	(Zulkifli & Rasit, 2020).
Aspergillus niger/ Penicillium sp.	Orange residue	Medications	(Athanázio-Heliodoro et al., 2018).
Penicillium sumatrense/ Aspergillus fumigatus	Sunflower Seed	Methyl Oleate	(Oliveira et al., 2020).
Anoxybacillus sp.	Mustard Pie	Detergent Manufacturing	(Sahoo et al., 2020).
Yarrowia lipolytica	Watermelon rinds	Depolymerization of polyethylene terephthalate (PET)	Sales, de Castro, Ribeiro & coelho, 2019
Candida viswanathii	Wheat bran with barley grain	Chicken Fat Hydrolysis	Almeida et al., 2016
Peniciliium polonicum	Sunflower seed	Bioremediation	Dickel et al., 2022

3.7 Environmental Importance of Microbial Lipases

Microbial lipases play a crucial role in environmental protection and sustainability through their various applications in bioremediation, waste treatment and biodiesel production. These enzymes are essential for the hydrolysis of lipids and other complex organic compounds, facilitating the degradation of environmental contaminants and the production of renewable energy (Ali et al., 2023).

Microbial lipases are widely used in the bioremediation of effluents rich in fatty acids and oils. They aid breaking of lipid pollutants, such as oils and fats, found in industrial and domestic wastewater (Bialeski et al., 2024). This process helps reduce the pollutant load, contributing to the purification of water bodies and protecting aquatic ecosystems.

In agro-industrial contexts, microbial lipases treat organic wastes, such as meal residues and used vegetable oils. These enzymes enable the conversion of waste into valuable products like biodiesel and bioactive compounds (Carvalho et al., 2024a; Carvalho et al., 2024b). The production of biodiesel from waste oils not only reduces reliance on fossil fuels but also supports sustainable waste management practices, further mitigating environmental impact (Hajjari et al., 2017).

Microbial lipases also minimize the environmental impact of chemical production and use. As highly specific and efficient biocatalysts, they reduce the need for harsh chemicals and lower the amount of generated waste, leading to a cleaner and safer environment (Ekeoma et al., 2023). In summary, microbial lipases are vital for environmental protection due to their ability to degrade contaminants, manage waste, and facilitate the production of renewable biodiesel. Their use significantly aids resource preservation and environmental impact reduction, supporting global sustainability and conservation goals (Abro et al., 2024).

4 CONCLUSIONS

Lipases are versatile enzymes that are critical as biocatalysts in various industrial applications. Utilizing agro-industrial wastes in solid-state fermentation allows for immobilizing lipases in fermented solids, enhancing their applicability across multiple sectors. This approach not only reduces the high costs typically associated with enzyme immobilization but also makes the process economically viable. The use of lipases in industrial processes aligns with the principles of green chemistry, offering several advantages, such as reduced by-product formation, high yields, the production of biodegradable products, and environmental safety. Additionally, their high recovery rates post-process contributes to minimizing environmental impacts. Numerous microorganisms have demonstrated effectiveness in various industrial applications, particularly when using agro-industrial residues rich in fatty acids. These residues are not only readily available but also offer diverse options that can be tailored to specific regional needs, further improving the feasibility and sustainability of the production process.

5 REFERENCES

Abol-Fotouh, D., AlHagar, O. E., Hassan, M. A. (2021). Optimization, purification, and biochemical characterization of thermoalkaliphilic lipase from a novel *Geobacillus stearothermophilus* FMR12 for detergent formulations. **International J of Biol Macromol** 181:125-135. DOI: https://doi.org/10.1016/j.ijbiomac.2021.03.111.

Abro, A. A., Qureshi, A. S., Khushk, I., Jatt, A. N., Ali, C. H., Karimi, K., Khan, M. S. Enhanced lipase production from ionic liquid tolerant Klebsiella aerogenes using mustard oilcake for efficient biodiesel production. **Renewable Energy**, p. 121143, 2024. DOI: https://doi.org/10.1016/j.renene.2024.121143.

Ali, S., Khan, S. A., Hamayun, M., & Lee, I. J. “The recent advances in the utility of microbial lipases: A review.” **Microorganisms** 11.2 (2023): 510. DOI: https://doi.org/10.3390/microorganisms11020510.

Aguieiras, E. C., Cavalcanti-Oliveira, E. D., Cammarota, M. C., Freire, D. M. (2018). Solid-state fermentation for the production of lipases for environmental and biodiesel applications. **Cur Develop in Biotec and Bioeng** 123-168. DOI: https://doi.org/10.1016/B978-0-444-63990-5.00008-6.

Alabdalall, A. H., ALanazi, A., Aldakeel, S. A., AbdulAzeez, S., Borgio, J. F. (2020). Molecular, physiological, and biochemical characterization of extracellular lipase production by *Aspergillus niger* using submerged fermentation. **PeerJ** 8:e9425.

Alami, N. H., Nasihah, L., Umar, R. L. A., Kuswytasari, N. D., Zulaika, E., Shovitri, M. (2017). Lipase production in lipolytic yeast from Wonorejo mangrove area. In: AIP Confer Proc. **AIP Publishing LLC** 020001. DOI: https://doi.org/10.1063/1.4985392.

Almeida, A. F., Dias, K. B., Da Silva, A. C. C., Terrasan, C. R. F., Tauk-Tornisielo, S. M., Carmona, E. C. (2016). Agroindustrial wastes as alternative for lipase production by *Candida viswanathii* under solid-state cultivation: purification, biochemical properties, and its potential for poultry fat hydrolysis. **Enz Res** 2016:1-15. DOI: http://dx.doi.org/10.1155/2016/1353497.

Amadi, O. C., Egong, E. J., Nwagu, T. N., Okpala, G., Onwosi, C. O., Chukwu, G. C., Moneke, A. N. (2020). Process optimization for simultaneous production of cellulase, xylanase and ligninase by *Saccharomyces cerevisiae* SCPW 17 under solid state fermentation using Box-Behnken experimental design. **Heliyon** 6:e04566. DOI:https://doi.org/10.1016/j.heliyon.2020.e04566.

Apriceno, A., Astolfi, M. L., Girelli, A. M., Scuto, F. R. (2019). A new laccase-mediator system facing the biodegradation challenge: insight into the NSAIDs removal. **Chemosphere** 215: 535-542. DOI: https://doi.org/10.1016/j.chemosphere.2018.10.086.

Arora, N. K., Mishra, J., Mishra, V. (2020). Microbial enzymes: roles and applications in industries. **Springer Nature** 11:331.

Athanázio-Heliodoro, J. C., Okino-Delgado, C. H., Fernandes, C. J. D. C., Zanutto, M. R., Prado, D. Z. D., Da Silva R, A., Facanali, R., Zambuzzi, W. F., Marques, M. M. O., Fleuri, L. F. (2018). Improvement of lipase obtaining system by orange waste-based solid-state fermentation: production, characterization and application. **Prepar Biochem and Biotec** 48:565-573. DOI: https://doi.org/10.1080/10826068.2018.1476879.

Bacha, A. B., Al-Assaf, A., Moubayed, N. M., Abid, I. (2018). Evaluation of a novel thermo-alkaline *Staphylococcus aureus* lipase for application in detergent formulations. **Saudi j of biol sci** 25: 409-417. DOI: https://doi.org/10.1016/j.sjbs.2016.10.006.

Balaji, L., Chittoor, J. T., Jayaraman, G. (2020). Optimization of extracellular lipase production by halotolerant *Bacillus* sp. VITL8 using factorial design and applicability of enzyme in pretreatment of food industry effluents. **Prepar biochem & biotec** 50:708-716. DOI: https://doi.org/10.1080/10826068.2020.1734936.

Barnes, N. M., Khodse, V. B., Lotlikar, N. P., Meena, R. M., Damare, S. R. (2018). Bioremediation potential of hydrocarbon-utilizing fungi from select marine niches of India. **3 Biotech**, 8:1-10. DOI: https://doi.org/10.1007/s13205-017-1043-8.

Bayramoglu, G., Celikbicak, O., Kilic, M., Arica, M. Y. (2022). Immobilization of *Candida rugosa* lipase on magnetic chitosan beads and application in flavor esters synthesis. **Food Chem** 366:130699.

Berekaa, M. M., Zaghloul, T. I., Abdel-Fattah, Y. R., Saeed, H. M., Sifour, M. (2019). Production of a novel glycerol-inducible lipase from thermophilic *Geobacillus stearothermophilus* strain-5. **World J of Microbiol and Biotec** 25:287-294. DOI: https://doi.org/10.1007/s11274-008-9891-3.

Bhan, C., Singh, J. (2020). Role of microbial lipases in transesterification process for biodiesel production. **Envir Sust** 1-10. DOI: https://doi.org/10.1007/s42398-020-00119-9.

Bharathi, D., Rajalakshmi, G., Komathi, S. (2018). Optimization and production of lipase enzyme from bacterial strains isolated from petrol spilled soil. **J of King Saud Univer-Sci** 31:898-901. DOI: https://doi.org/10.1016/j.jksus.2017.12.018.

Bharathi, D., Rajalakshmi, G. (2019). Microbial lipases: An overview of screening, production and purification. **Biocat and Agric Biotec** 22:101368. DOI: https://doi.org/10.1016/j.bcab.2019.101368.

Bialeski, D. D., Triques, C. C., Carvalho, J. K., Rodrigues, M. L. F., Dall'Oglio, I. C., Silva-Lucca, R. A., Fagundes-Klen, M. R. Natural Coagulant Functionalized with Magnetic Nanoparticles Better Treated Dairy Wastewater Compared to Bioremediation. **Waste and Biomass Valorization**, p. 1-13, 2024. DOI: https://doi.org/10.1007/s12649-024-02585-2.

Bom, M. A. T., Botton, V., Altheia, F. M., Thomas, J. C., Piovan, L., Córdova, J., Michell, D. A., Krieger, N. (2021). Fermented solids that contain lipases produced by *Rhizopus microsporus* have an S-enantiopreference in the resolution of secondary alcohols. **Biochem Eng J** 165:107817. DOI: https://doi.org/10.1016/j.bej.2020.107817.

Botton, V., Piovan, L., Meier, H. F., Mitchell, D. A., Cordova, J., Krieger, N. (2018). Optimization of biodiesel synthesis by esterification using a fermented solid produced by *Rhizopus microsporus* on sugarcane bagasse. **Biopr and biosyst eng** 41:573-583. DOI: https://doi.org/10.1007/s00449-018-1892-5.

Bouaziz, A., Horchani, H., Salem, N. B., Gargouri, Y., Sayari, A. (2011). Expression, purification of a novel alkaline *Staphylococcus xylosus* lipase acting at high temperature. **Biochem eng j** 54:93-102. DOI: https://doi.org/10.1016/j.bej.2011.02.003.

Brabcová, J., Demianová, Z., Vondrášek, J., Jágr, M., Zarevúcka, M., Palomo, J. M. (2013). Highly selective purification of three lipases from *Geotrichum candidum* 4013 and their characterization and biotechnological applications. **J of Mol Catal B: Enzy** 98:62-72. DOI: https://doi.org/10.1016/j.molcatb.2013.09.012.

Cai, Y. D., Chou, K. C. (2005). Predicting Enzyme Subclass by Functional Domain Composition and Pseudo Amino Acid Composition. *J of prot res* 4:967-971. DOI: https://doi.org/10.1021/pr0500399.

Çakmak, M., Aydoğdu, H. (2021). Screening of microfungi for lipolytic activity and optimization of process parameters in lipase production by solid substrate fermentation using selected microfungi (*Penicillium aurantiogriseum*). **Kuwait J of Sci** 48:98-105.

Cao, X., Pan, Y., Wei, W., Yuan, T., Wang, S., Xiang, L., Yuan, Y. (2021). Single cell oil production by *Trichosporon sp.* Effects of fermentation conditions on fatty acid composition and applications in synthesis of structured triacylglycerols. **LWT** 148:111691.

Carteret, C., Jacoby, J., Blin, J. L. (2018). Using factorial experimental design to optimize biocatalytic biodiesel production from *Mucor Miehei* Lipase immobilized onto ordered mesoporous materials. **Microp and Mesop Mat** 268:39-45. DOI: https://doi.org/10.1016/j.micromeso.2018.04.004.

Carpen, A., Bonomi, F., Iametti, S., Marengo, M. (2019). Effects of starch addition on the activity and specificity of food-grade lipases. **Biotec and app biochem** 66:607-616. DOI: https://doi.org/10.1002/bab.1761.

Carvalho, J. K., Panatta, A. A. S., Silveira, M. A. D., Tav, C., Johann, S., Rodrigues, M. L. F., Martins, C. V. B. (2021). Yeasts isolated from a lotic continental environment in Brazil show potential to produce amylase, cellulase and protease. **Biotec Reports** 30:e00630. DOI: https://doi.org/10.1016/j.btre.2021.e00630.

Carvalho, J. K., Krüger, C., Silveira, M. A. D., Piana, P. A., Rodrigues, M. L. F., Rosado, A. F., Zanella, R. A.Lipolytic production from solid-state fermentation of the filamentous fungus *Penicillium polonicum* and its applicability as biocatalyst in the synthesis of ethyl oleate. **Environmental Science and Pollution Research**, v. 31, n. 19, p. 28632-28643, 2024. DOI: https://doi.org/10.1007/s11356-024-33007-4.

Carvalho, J. K., Zanella, R. A., Piana, P. A., Rosado, A. F., da Silva, M. D., Lucca, R. A. D. S. D., Rodrigues, M. L. F. Production of Fermented Solid Containing Lipases from Penicillium polonicum and Its Direct Use as Biocatalyst in the Synthesis of Ethyl Oleate. **BioEnergy Research**, p. 1-10, 2024. DOI: https://doi.org/10.1007/s12155-024-10772-1.

Çakmak, M., Aydoğdu, H. (2021). Screening of microfungi for lipolytic activity and optimization of process parameters in lipase production by solid substrate fermentation using selected microfungi (*Penicillium aurantiogriseum*). **Kuwait J of Sci** 48: 98-105.

Chakraborty, K., Raj, R. P. (2008). An extra-cellular alkaline metallolipase from *Bacillus licheniformis* MTCC 6824: purification and biochemical characterization. **Food chem**. 109:727-736. DOI: https://doi.org/10.1016/j.foodchem.2008.01.026.

Chandra, P., Singh, R., Arora, P. K. (2020). Microbial lipases and their industrial applications: a comprehensive review. *Microbial Cell Fact* 19:1-42. DOI: https://doi.org/10.1186/s12934-020-01428-8.

Colla, L. M., Ficanha, A. M., Rizzardi, J., Bertolin, T. E., Reinehr, C. O., Costa, J. A. V. (2015). Production and characterization of lipases by two new isolates of Aspergillus through solid-state and submerged fermentation. **BioMed Res Inter** 2015. DOI: https://doi.org/10.1155/2015/725959.

Czaja, R. (2015). Cluster-Screening - eine effiziente Methode zur Identifizierung neuer Enzyme. **BioSpektrum** 21:344-346.

De Souza, C. E. C., Ribeiro, B. D., Coelho, M. A. Z. (2019). Characterization and application of *Yarrowia lipolytica* lipase obtained by solid-state fermentation in the synthesis of different esters used in the food industry. **App biochem and biotec** 189:933-959. DOI: https://doi.org/10.1007/s12010-019-03047-5.

Deng, Z., Jiang, Y., Chen, K., Li, J., Zheng, C., Gao, F., Liu, X. (2020). One Biosurfactant-Producing Bacteria *Achromobacter sp.* A-8 and Its Potential Use in Microbial Enhanced Oil Recovery and Bioremediation. **Frontiers in microbio** 11:247. DOI: https://doi.org/10.3389/fmicb.2020.00247.

Dickel, J. D. M, Carvalho, J. K., Silveira, M. A. D., Menegotto dos Santos, P., Rodrigues, M. L. F., Fagundes-Klen, M. R., Rosa, C. A., Buzanello, C. V., Lucca, R. A. S., Santos, A. R. O., Da Rosa, M. F. Aspergillus sclerotiorum lipolytic activity and its application in bioremediation of high-fat dairy wastewater environments. **Environmental Science and Pollution Research**. 1-11, 2022. https://doi.org/10.1007/s11356-022-24669-z.

Divya, K., Padma, P. N. (2015). Psychrophilic yeast isolates for cold-active lipase production. **Int. J. Sci. Prog. Res** 10:93-97.

Doble, M., Rollins, K., Kumar, A. **Green chemistry and engineering**. Academic Press, 2010.

Durval, I. J. B., Mendonça, A. H. R., Rocha, I. V., Luna, J. M., Rufino, R. D., Converti, A., Sarubbo, L. A. (2020). Production, characterization, evaluation and toxicity assessment of a *Bacillus cereus* UCP 1615 biosurfactant for marine oil spills bioremediation. **Marine Pol Bulletin** 157:111357. DOI: https://doi.org/10.1016/j.marpolbul.2020.111357.

Ebrahimpour, A., Abd Rahman, R. N. Z. R., Ch'ng, D. H. E., Basri, M., Salleh, A. B. (2008). A modeling study by response surface methodology and artificial neural network on culture parameters optimization for thermostable lipase production from a newly isolated thermophilic *Geobacillus sp*. strain ARM. **BMC biotec** 8:1-15. DOI: https://doi.org/10.1186/1472-6750-8-96.

Edwinoliver, N. G., Thirunavukarasu, K., Naidu, R. B., Gowthaman, M. K., Kambe, T. N., Kamini, N. R. (2010). Scale up of a novel tri-substrate fermentation for enhanced production of *Aspergillus niger* lipase for tallow hydrolysis. *Biores Tec* 101:6791-6796. DOI: https://doi.org/10.1016/j.biortech.2010.03.091.

Ekeoma, B. C., Ekeoma, L. N., Yusuf, M., Haruna, A., Ikeogu, C. K., Merican, Z. M. A., Chelliapan, S. Recent advances in the biocatalytic mitigation of emerging pollutants: a comprehensive review. **Journal of biotechnology**, v. 369, p. 14-34, 2023. DOI: https://doi.org/10.1016/j.jbiotec.2023.05.003.

Farinas, C. S. (2015). Developments in solid-state fermentation for the production of biomass-degrading enzymes for the bioenergy sector. **Renew and Sust Ener Rev** 52:179-188. DOI: https://doi.org/10.1016/j.rser.2015.07.092.

Fatima, S., Faryad, A., Ataa, A., Joyia, F. A., Parvaiz, A. (2021). Microbial lipase production: A deep insight into the recent advances of lipase production and purification techniques. **Biotec and App Biochem** 68:445-458. DOI: https://doi.org/10.1002/bab.2019.

Feng, K., Huang, Z., Peng, B., Dai, W., Li, Y., Zhu, X., Chen, Y., Tong, X., Lan, Y., Cao, Y. (2020). Immobilization of *Aspergillus niger* lipase onto a novel macroporous acrylic resin: Stable and recyclable biocatalysis for deacidification of high-acid soy sauce residue oil. **Biores Tec** 298:122553. DOI: https://doi.org/10.1016/j.biortech.2019.122553.

Fonseca, J. M., Teleken, J. G., De Cinque Almeida, V., Da Silva, C. (2019). Biodiesel from waste frying oils: Methods of production and purification. **Ener Conver and Manag** 184:205-218. DOI: https://doi.org/10.1016/j.enconman.2019.01.061.

Galeano, J. D., Mitchell, D. A., Krieger, N. (2017). Biodiesel production by solvent-free ethanolysis of palm oil catalyzed by fermented solids containing lipases of *Burkholderia* contaminans. **Biochem Eng J** 127:77-86. DOI: https://doi.org/10.1016/j.bej.2017.08.008.

Gao, B., Xu, T., Lin, J., Zhang, L., Su, E., Jiang, Z., Wei, D. (2011). Improving the catalytic activity of lipase LipK107 from *Proteus sp*. by site-directed mutagenesis in the lid domain based on computer simulation. **J of Mol Catalysis B: Enz** 68:286-291. DOI: https://doi.org/10.1016/j.molcatb.2010.12.001.

García-Silvera, E. E., Martínez-Morales, F., Bertrand, B., Morales-Guzmán, D., Rosas-Galván, N. S., León-Rodríguez, R., Trejo-Hernández, M. R. (2018). Production and application of a thermostable lipase from Serratia marcescens in detergent formulation and biodiesel production. **Biotec and app biochem** 65:156-172. https://doi.org/10.1002/bab.1565.

Geoffry, K., Achur, R. N. (2018). Screening and production of lipase from fungal organisms. **Bioc and agric biotec** 14:241-253. DOI: https://doi.org/10.1016/j.bcab.2018.03.009.

Girelli, A. M., Astolfi, M. L., Scuto, F. R. (2019). Agro-industrial wastes as potential carriers for enzyme immobilization: A review. **Chemosphere** 244:125368. DOI: https://doi.org/10.1016/j.chemosphere.2019.125368.

Grajales-Hernández, D. A., Velasco-Lozano, S., Armendáriz-Ruiz, M. A., Rodríguez-González, J. A., Camacho-Ruíz, R. M., Asaff-Torres, A., Mateos-Díaz, J. C. (2020). Carrier-bound and carrier-free immobilization of type A feruloyl esterase from *Aspergillus niger*: Searching for an operationally stable heterogeneous biocatalyst for the synthesis of butyl hydroxycinnamates. **J of Biotec** 316:6-16. DOI: https://doi.org/10.1016/j.jbiotec.2020.04.004.

Grbavčić, S., Bezbradica, D., Izrael-Živković, L., Avramović, N., Milosavić, N., Karadžić, I., Knežević-Jugović, Z. (2011). Production of lipase and protease from an indigenous *Pseudomonas aeruginosa* strain and their evaluation as detergent additives: compatibility study with detergent ingredients and washing performance. **Bior Tech** 102:11226-11233. DOI: https://doi.org/10.1016/j.biortech.2011.09.076.

Guncheva, M., Zhiryakova, D. (2011). Catalytic properties and potential applications of *Bacillus* lipases. **J of Mol Catalysis B: Enz** 68:1-21. DOI: https://doi.org/10.1016/j.molcatb.2010.09.002.

Gutarra, M. L., Godoy, M. G., Maugeri, F., Rodrigues, M. I., Freire, D. M., Castilho, L. R. (2009). Production of an acidic and thermostable lipase of the mesophilic fungus *Penicillium simplicissimum* by solid-state fermentation. *Bior tec* 100:5249-5254. DOI: https://doi.org/10.1016/j.biortech.2008.08.050.

Hajjari, M., Tabatabaei, M., Aghbashlo, M., Ghanavati, H. A review on the prospects of sustainable biodiesel production: A global scenario with an emphasis on waste-oil biodiesel utilization. **Renewable and Sustainable Energy Reviews**, v. 72, p. 445-464, 2017. DOI: https://doi.org/10.1016/j.rser.2017.01.034.

Hama, S., Noda, H., Kondo, A. (2018). How lipase technology contributes to evolution of biodiesel production using multiple feedstocks. **Cur op in biotec** 50:57-64. DOI: https://doi.org/10.1016/j.copbio.2017.11.001.

Javed, S., Azeem, F., Hussain, S., Rasul, I., Siddique, M. H., Riaz, M., Afzal, M., Kouser, A., Nadeem, H. (2018). Bacterial lipases: a review on purification and characterization. **Prog in biophys and mol biol** 132:23-34. DOI: https://doi.org/10.1016/j.pbiomolbio.2017.07.014.

Joshi, R., Sharma, R., Kuila, A. (2019). Lipase production from *Fusarium incarnatum* KU377454 and its immobilization using Fe_3 O_4 NPs for application in waste cooking oil degradation. **Bior Tec Reports** 5:134-140. DOI: https://doi.org/10.1016/j.biteb.2019.01.005.

Kartal, F. (2016). Enhanced esterification activity through interfacial activation and cross-linked immobilization mechanism of *Rhizopus oryzae* lipase in a nonaqueous medium. **Biotec progress** 32:899-904. DOI: https://doi.org/10.1002/btpr.2288.

Khan, F. I., Lan, D., Durrani, R., Huan, W., Zhao, Z., Wang, Y. (2017). The lid domain in lipases: structural and functional determinant of enzymatic properties. **Front in bioeng and biotec** 5:16. DOI: https://doi.org/10.3389/fbioe.2017.00016.

Khosla, K., Rathour, R., Maurya, R., Maheshwari, N., Gnansounou, E., Larroche, C., Thakur, I. S. (2017). Biodiesel production from lipid of carbon dioxide sequestrating bacterium and lipase of psychrotolerant *Pseudomonas sp*. ISTPL3 immobilized on biochar. **Bior tec** 245:743-750. DOI: https://doi.org/10.1016/j.biortech.2017.08.194.

Kreling, N. E., Simon, V., Fagundes, V. D., Thomé, A., Colla, L. M. (2020). Simultaneous production of lipases and biosurfactants in solid-state fermentation and use in bioremediation. **J of Envir Eng** 146:04020105.

Kuhlmann, J., Kretschmann, A. C., Bester, K., Bollmann, U. E., Dalhoff, K., Cedergreen, N. (2019). Enantioselective mixture toxicity of the azole fungicide imazalil with the insecticide α-cypermethrin in *Chironomus riparius*: Investigating the importance of toxicokinetics and enzyme interactions. **Chemosphere** 225:166-173. DOI: https://doi.org/10.1002/bab.1394.

Kumar, D., Das, T., Giri, B. S., Verma, B. (2020). Preparation and characterization of novel hybrid bio-support material immobilized from *Pseudomonas cepacia* lipase and its application to enhance biodiesel production. **Renew Ener** 147:11-24. DOI: https://doi.org/10.1016/j.renene.2019.08.110.

Kumura, H., Satoh, M., Machiya, T., Hosono, M., Hayakawa, T., Wakamatsu, J. I. (2019). Lipase and protease production of dairy *Penicillium sp*. on milk-protein-based solid substrates. **Inter j of dairy tec** 72: 403-408.https://doi.org/10.1111/1471-0307.12597.

Lan, D., Qu, M., Yang, B., Wang, Y. (2016). Enhancing production of lipase MAS1 from marine

Streptomyces sp. strain in Pichia pastoris by chaperones co-expression. **Elec J of Biotec** 22:62-67. DOI: https://doi.org/10.1016/j.ejbt.2016.06.003.

Lee, L. P., Karbul, H. M., Citartan, M., Gopinath, S. C., Lakshmipriya, T., Tang, T. H. (2015). Lipase-secreting *Bacillus* species in an oil-contaminated habitat: promising strains to alleviate oil pollution. **BioMed res inter** 2015. DOI: https://doi.org/10.1155/2015/820575.

López-Fernández, J., Benaiges, M. D., Valero, F. (2020). *Rhizopus oryzae* lipase, a promising industrial enzyme: Biochemical characteristics, production and biocatalytic applications. **Catalysts** 10:1277. DOI: https://doi.org/10.3390/catal10111277.

Madzak, C. (2018). Engineering *Yarrowia lipolytica* for use in biotechnological applications: a review of major achievements and recent innovations. **Mol biotec** 60:621-635.

Maharana, A. K., Singh, S. M. (2018). A cold and organic solvent tolerant lipase produced by Antarctic strain *Rhodotorula sp*. Y-23. **J of basic microbiol** 58:331-342.

Mahmoud, G. A., Koutb, M. M., Morsy, F. M., Bagy, M. M. (2015). Characterization of lipase enzyme produced by hydrocarbons using fungus *Aspergillus terreus*. **Eur J of Biol Res** 5:70-77.

Massoud, R., Hadiani, M. R., Hamzehlou, P., Khosravi-Darani, K. (2019). Bioremediation of heavy metals in food industry: Application of Saccharomyces cerevisiae. **Elec J of Biotec** 37:56-60. DOI: https://doi.org/10.1016/j.ejbt.2018.11.003.

Melani, N. B., Tambourgi, E. B., Silveira, E. (2020). Lipases: from production to applications. **Sep & Pur Reviews** 49:143-158. DOI: https://doi.org/10.1080/15422119.2018.1564328.

Moftah, O. A. S., Grbavčić, S., Žuža, M., Luković, N., Bezbradica, D., Knežević-Jugović, Z. (2012). Adding value to the oil cake as a waste from oil processing industry: production of lipase and protease by *Candida* utilis in solid state fermentation. **App biochem and biotec** 166:348-364. DOI: https://doi.org/10.1007/s12010-011-9429-2.

Monteiro, R. R., Virgen-Ortiz, J. J., Berenguer-Murcia, A., Da Rocha, T. N., Dos Santos, J. C., Alcantara, A. R., Fernandez-Lafuente, R. (2021). Biotechnological relevance of the lipase A from *Candida antarctica*. **Cat Today** 362:141-154.

Nagarajan, S. (2012). New tools for exploring “old friends-microbial lipases”. **App biochem and biotec** 168:1163-1196. DOI: https://doi.org/10.1007/s12010-012-9849-7.

Naghdi, M., Taheran, M., Brar, S. K., Kermanshahi-Pour, A., Verma, M., Surampalli, R. Y. (2018). Removal of pharmaceutical compounds in water and wastewater using fungal oxidoreductase enzymes. **Env pol** 234:190-213. DOI: https://doi.org/10.1016/j.envpol.2017.11.060.

Niyonzima, F. N., More, S. S. (2014). Detergent-compatible bacterial amylases. **App biochem and biotec** 174:1215-1232. DOI: https://doi.org/10.1007/s12010-014-1144-3.

Oliveira, F., Souza, C. E., Peclat, V. R., Salgado, J. M., Ribeiro, B. D., Coelho, M. A., Venancio, A., Belo, I. (2017). Optimization of lipase production by *Aspergillus ibericus* from oil cakes and its application in esterification reactions. **Food and Biop Proc** 102:268-277. DOI: https://doi.org/10.1016/j.fbp.2017.01.007.

Oliveira, A. C. D., Frensch, G., De Assis Marques, F., Vargas, J. V. C., Rodrigues, M. L. F., Mariano, A. B. (2020). Production of methyl oleate by direct addition of fermented solid *Penicillium sumatrense* and *Aspergillus fumigatus*. **Renew Energy** 162:1132-1139. DOI: https://doi.org/10.1016/j.renene.2020.08.117.

Ostojčić, M., Budžaki, S., Flanjak, I., Bilić. R. B., Barišić, I., Tran, N. N., Hessel, V., Strelec, I. (2021). Production of biodiesel by *Burkholderia cepacia* lipase as a function of process parameters. **Biotec Prog** 37:e3109. DOI: https://doi.org/10.1002/btpr.3109.

Paluzar, H., Tuncay, D., Aydogdu, H. (2021). Production and characterization of lipase from *Penicillium aurantiogriseum* under solid-state fermentation using sunflower pulp. **Bioc and Biotrans** 39:333-342. DOI: https://doi.org/10.1080/10242422.2021.1901888.

Poppe, J. K., Garcia-Galan, C., Matte, C. R., Fernandez-Lafuente, R., Rodrigues, R. C., Ayub, M. A. Z. (2013). Optimization of synthesis of fatty acid methyl esters catalyzed by lipase B from *Candida antarctica* immobilized on hydrophobic supports. **J of Mol Catalysis B: Enz** 94:51-56. DOI: https://doi.org/10.1016/j.molcatb.2013.05.010.

Prabaningtyas, R. K., Putri, D. N., Utami, T. S., Hermansyah, H. (2018). Production of immobilized extracellular lipase from *Aspergillus niger* by solid state fermentation method using palm kernel cake, soybean meal, and coir pith as the substrate. **Ener Procedia** 153:242-247. DOI: https://doi.org/10.1016/j.egypro.2018.10.010.

Preczeski, K. P., Kamanski, A. B., Scapini, T., Camargo, A. F., Modkoski, T. A., Rossetto, V., Venturin, B., Mulinari, J., Golunski, S. M., Mossi, A. J., Treichel, H. (2018). Efficient and low-cost alternative of lipase concentration aiming at the application in the treatment of waste cooking oils. **Biopr and biosyst eng** 41:851-857. DOI: https://doi.org/10.1007/s00449-018-1919-y.

Priyanka, P., Tan, Y., Kinsella, G. K., Henehan, G. T., Ryan, B. J. (2019). Solvent stable microbial lipases: current understanding and biotechnological applications. **Biotec letters** 41:203-220. DOI: https://doi.org/10.1007/s10529-018-02633-7.

Ramos-Sánchez, L. B., Cujilema-Quitio, M. C., Julian-Ricardo, M. C., Cordova, J., Fickers, P. (2015). Fungal lipase production by solid-state fermentation. **J of Biop & Biotec** 5:1. DOI: 10.4172/2155-9821.1000203.

Rana, K. L., Kour, D., Sheikh, I., Dhiman, A., Yadav, N., Yadav, A. N., Rastegari, A. A., Singh, K., Saxena, A. K. (2019). Endophytic fungi: biodiversity, ecological significance, and potential industrial applications. In: Recent advancement in white biotechnology through fungi. **Springer, Cham** 1-62. DOI: https://doi.org/10.1007/978-3-030-10480-1_1.

Roy, M., Kumar. R., Ramteke, A., Sit, N. (2021). Identification of lipase producing fungus isolated from dairy waste contaminated soil and optimization of culture conditions for lipase production by the isolated

fungus. **Jof Microbiol, Biotec and Food Sci** 2021:698-704. DOI: 10.15414/jmbfs.2018.8.1.698-704.
Sadh, P. K., Duhan, S., Duhan, J. S. (2018). Agro-industrial wastes and their utilization using solid state fermentation: a review. **Bior and Biop** 5:1-15. DOI: https://doi.org/10.1186/s40643-017-0187-z.

Sagar, K., Bashir, Y., Phukan, M. M., Konwar, B. K. (2013). Isolation of lipolytic bacteria from waste contaminated soil: A study with regard to process optimization for lipase. **Int. J. Sci. Technol. Res**, 2(10)214-218.

Sahoo, R. K., Das, A., Gaur, M., Sahu, A., Sahoo, S., Dey, S., Rahman, P. K. S. M., Subudhi, E. (2020). Parameter optimization for thermostable lipase production and performance evaluation as prospective detergent additive. **Prep Biochem & Biotec** 50:578-584. DOI: https://doi.org/10.1080/10826068.2020.1719513.

Sales, J. C. S., De Castro, A. M., Ribeiro, B. D. Z., Coelho, M. A. (2020). Supplementation of watermelon peels as an enhancer of lipase and esterase production by *Yarrowia lipolytica* in solid-state fermentation and their potential use as biocatalysts in poly (ethylene terephthalate) (PET) depolymerization reactions. **Bioc and Biotrans** 38:457-468. DOI: https://doi.org/10.1080/10242422.2020.1782387.

Salum, T. F. C., Villeneuve, P., Barea, B., Yamamoto, C. I., Côcco, L. C., Mitchell, D. A., Krieger, N. (2010). Synthesis of biodiesel in column fixed-bed bioreactor using the fermented solid produced by Burkholderia cepacia LTEB11. **Process Biochem** 45:1348-1354.

Sangkharak, K., Mhaisawat, S., Rakkan, T., Paichid, N., Yunu, T. (2020). Utilization of mixed chicken waste for biodiesel production using single and combination of immobilized lipase as a catalyst. **Biomass Conver and Bioref** 1-14. DOI: https://doi.org/10.1007/s13399-020-00842-7.

Sarmah, N., Revathi, D., Sheelu, G., Yamuna, Rani. K., Sridhar, S., Mehtab, V., Sumana, C. (2018). Recent advances on sources and industrial applications of lipases. **Biotec progress** 34:5-28. DOI: https://doi.org/10.1002/btpr.2581.

Shahedi, M., Yousefi, M., Habibi, Z., Mohammadi, M., As' habi, M. A. (2019). Co-immobilization of *Rhizomucor miehei* lipase and *Candida antarctica* lipase B and optimization of biocatalytic biodiesel production from palm oil using response surface methodology. **Renew Energy** 141: 847-857.

Shakerian, F., Zhao, J., LI Shao-Ping. (2020). Recent development in the application of immobilized oxidative enzymes for bioremediation of hazardous micropollutants-A review. **Chemosphere** 239:124716. DOI: https://doi.org/10.1016/j.chemosphere.2019.124716.

Singh, A. K., Mukhopadhyay, M. (2012). Overview of fungal lipase: a review. **App biochem and biotec** 166:486-520. DOI: https://doi.org/10.1007/s12010-011-9444-3.

Soares, D., Pinto, A. F., Gonçalves, A. G., Mitchell, D. A., Krieger, N. Biodiesel production from soybean soapstock acid oil by hydrolysis in subcritical water followed by lipase-catalyzed esterification using a fermented solid in a packed-bed reactor. **Biochem Eng J** 81:15-23. DOI: https://doi.org/10.1016/j.bej.2013.09.017.

Soccol, C. R., Da Costa, E. S. F., Letti, L. A. J., Karp, S. G., Woiciechowski, A. L., De Souza, V. L. P.

(2017). Recent developments and innovations in solid state fermentation. **Biotec Res and Innov** 1:52-71. DOI: https://doi.org/10.1016/j.biori.2017.01.002.

Souza, C. E. C., Ribeiro, B. D., Coelho, M. A. Z. (2019). Characterization and application of *Yarrowia lipolytica* lipase obtained by solid-state fermentation in the synthesis of different esters used in the food industry. **App biochem and biotec** 189: 933-959.

Steudler, S., Werner, A., Walther, T. (2019). t is the mix that matters: Substrate-specific enzyme production from filamentous fungi and bacteria through solid-state fermentation. **Sol State Ferment** 51-81. DOI: https://doi.org/10.1007/10_2019_85.

Su, Y., Liu, C., Fang, H., Zhang, D. (2020). Bacillus subtilis: a universal cell factory for industry, agriculture, biomaterials and medicine. **Microb Cell Fact** 19:1-12. DOI: https://doi.org/10.1186/s12934-020-01436-8.

Subroto, E., Indiarto, R., Pangawikan, A. D., Huda, S., Yarlina, V. P. (2020). Characteristics, immobilization, and application of *Candida rugosa* lipase. **Food Res** 4:1391-1401.

Taheri-Kafrani, A., Kharazmi, S., Nasrollahzadeh, M., Soozanipour, A., Ejeian, F., Etedali, P., Mansouri-Tehrani, H. A., Razmjou, A., Yek, S. M. G., Varma, R. S. (2021). Recent developments in enzyme immobilization technology for high-throughput processing in food industries. **Critical Rev in Food Sci and Nutr** 61:3160-3196. DOI: https://doi.org/10.1080/10408398.2020.1793726.

Tambunan, U. S. F., Randy, A., Parikesit, A. A. (2014). Design of *Candida antarctica* lipase B thermostability improvement by introducing extra disulfide bond into the enzyme. **On J of Biol Sci** 14:108-118.

Tan, T., Lu, J., Nie, K., Deng, L., Wang, F. (2010). Biodiesel production with immobilized lipase: a review. **Biotec adv** 28:628-634. DOI: https://doi.org/10.1016/j.biotechadv.2010.05.012.

Tao, Z., Dong, B., Teng, Z., Zhao, Y. (2020). he classification of enzymes by deep learning. **IEEE Access** 8:89802-89811. DOI:10.1109/ACCESS.2020.2992468.

Thapa, S., Li, H., OHair, J., Bhatti, S., Chen, F. C., Al, Nasr. K., Johnson, T., Zhou, S. (2019). Biochemical characteristics of microbial enzymes and their significance from industrial perspectives. **Mol biotec** 61:579-601. DOI: https://doi.org/10.1007/s12033-019-00187-1.

Tong, X., Busk, P. K., Lange, L. (2015). Characterization of a new sn-1, 3-regioselective triacylglycerol lipase from Malbranchea cinnamomea. **Biotec and app biochem** 63:471-478. DOI: https://doi.org/10.1002/bab.1394.

Utami, T. S., Hariyani, I., Alamsyah, G., Hermansyah, H. (2017). Production of dry extract extracellular lipase from *Aspergillus niger* by solid state fermentation method to catalyze biodiesel synthesis. **Energy Procedia** 136:41-46. DOI: https://doi.org/10.1016/j.egypro.2017.10.275.

Vandenberghe, L. P., Pandey, A., Carvalho, J. C., Letti, L. A., Woiciechowski, A. L., Karp, S. G., Thomaz-Soccol, V., Martínez-Burgos, W. J., Penha, R. O., Hermann, L. W., Rodrigues, A. O., Soccol, C. R. (2021). Solid-state fermentation technology and innovation for the production of agricultural and animal feed bioproducts. **Syst Microbiol and Bioman** 1:142-165. DOI: https://doi.org/10.1007/s43393-020-00015-7.

Vyas, S., Chhabra, M. (2017). Isolation, identification and characterization of *Cystobasidium oligophagum* JRC1: A cellulase and lipase producing oleaginous yeast. **Bior tec** 223:250-258. DOI: https://doi.org/10.1016/j.biortech.2016.10.039.

Wadia, T., Jain, S. K. (2017). Isolation, screening and identification of lipase producing fungi from oil contaminated soil of Shani Mandir Ujjain. **Inter j of curt microbiol and app sci** 6:1872-1878. DOI: 10.20546/ijcmas.2017.607.223.

Zhang, Y., He, S., Simpson, B. K. (2018). Enzymes in food bioprocessing-novel food enzymes, applications, and related techniques. **Cur opin in food sci** 19:30-35. DOI: https://doi.org/10.1016/j.cofs.2017.12.007.

Zhong, L., Feng, Y., Wang, G., Wang, Z., Bilal, M., Lv, H., Hexin, L. V., Jia, C. J. (2020). Production and use of immobilized lipases in/on nanomaterials: A review from the waste to biodiesel production. **Inter j of biol macromol** 152:207-222. DOI: https://doi.org/10.1016/j.ijbiomac.2020.02.258.

Zulkifli, N. N., Rasit, N. (2020). Lipase production from solid state fermentation of copra waste associated fungus *Aspergillus niger*. *UMT J of Underg* **Res** 2:2.